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OBSERVATIONS OF BREAKUP ON THE ATHABASCA RIVER NEAR FORT MCMURRAY, 1986 and 1987

by

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ABSTRACT

This report summarizes the 1986 and 1987 ice jam observations on the Athabasca River at Fort McMurray between Mountain Rapids and Suncor. To further enhance present knowledge of ice jam characteristics, the data gathered during these two events have been analyzed and compared with accepted theories in river ice hydraulics.

Breakup in both years was relatively uneventful for the resident of Fort McMurray. Although jamming did occur downstream of the city during each year, either the flows in the river or the supply of ice were insufficient to produce a jam that was large enough to cause flooding. The maximum observed stage for 1986 and 1987 at the mouth of the Clearwater River was 244.0 m and 244.5 m, respectively. This in the order of 1.0 m below bankful stage on the Clearwater River.

The 1986 jam had total length of about 16 km and an average height of approximately 6.5 m. The formative discharge is estimated to have been 540 m^3/s, of which 90 m^3/s was contributed by the Clearwater River. Computations indicate that the thickness of the equilibrium section of the jam was about 3.6 m. The jam roughness and coefficient of internal friction were found to be 0.074 and 1.1, respectively; consistent with those determined for the other documented jams along the river.

The 1987 jam, about 11 km in length, was extremely unstable with an average height of about 6.4 m within the equilibrium section. Measurements of the shear walls suggested an equilibrium thickness ranging between 3 and 5 m. Unfortunately the discharge for the event could not be estimated and the complete analysis could not be done. Upon destruction, the 1987 jam produced a surge of water which moved downstream into a channel almost clear of ice. This surge attenuated rapidly and at a distance of 7 km downstream of the location of the initially formed toe, the height of the surge was about one half that of the height of the jam. At a distance of 17 km downstream the effects of the surge were almost imperceptible.

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P. Mostert, G. Van Der Vinne, and J. Thompson of the Resource Technologies Department, Alberta Research Council performed much of the field work. L. Sheppard typed the final manuscript. G. Fonstad reviewed the final draft.

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1.0 INTRODUCTION

The City of Fort McMurray, situated at the confluence of the Athabasca and Clearwater Rivers in northeastern Alberta, is susceptible to occasional spring flooding. The primary cause of this flooding is the accumulation and jamming of large masses of ice in the Athabasca River channel below the confluence. This results in the backup of water in both rivers and consequently, inundation of low lying areas within the community.

The most recent flooding at Fort McMurray occurred in late April of 1979. Since then considerable effort has been spent both observing breakup processes along the Athabasca River and documenting the hydraulic characteristics of the associated ice jams (Doyle and Andres, 1979; Andres and Doyle, 1984; Andres and Rickert, 1984, 1985a, 1985b).

The purpose of this report is to summarize the 1986 and 1987 breakup observations made between Mountain Rapids and the Suncor Oil Sands Development approximately 14 km upstream and 27 km downstream of Fort McMurray, respectively. To further enhance present knowledge of ice jam characteristics in this stretch of the Athabasca River, ice jam data gathered during these two events have also been analyzed and compared with accepted theories in river ice hydraulics.

2.0 STUDY AREA

2.1 Hydrologic Characteristics

The Athabasca River originates in the Rocky Mountains about 280 km southwest of Edmonton and flows in a northeasterly direction across the province into Lake Athabasca (figure 1). The river is over 1400 km long and at its mouth, has a drainage area of more than 155,000 km^2. Above the Clearwater River confluence at Fort McMurray, the drainage basin area is approximately 98,000 km^2.

Both the Athabasca and Clearwater River flows in the Fort McMurray area have been continuously recorded by Water Survey of Canada (WSC) since 1958. The gauge on the Athabasca River (07DA001) is located about 3.5 km downstream of the confluence. The gauge on the Clearwater River (07DC001) is located near Draper, some 18 km upstream of the confluence. Mean annual discharge at these sites are about 680 and 130 m^3/s, respectively.

The climate in the area is typically continental with warm summers and cold winters. Spring and fall tend to be short, as temperature changes rapidly during these transitional seasons. Average annual precipitation is about 430 mm with more than half of this total occurring in June, July and August. Average annual daily maximum and minimum temperatures are about 5°C and -7°C, respectively. The ice cover on the Athabasca River typically forms between late October and mid-November and then usually remains intact until at least mid-April. Flows during the intervening period are low and relatively steady during most years, ranging from about 150 to 200 m^3/s at the gauge below Fort McMurray.

Because the Clearwater River basin extends eastward into Saskatchewan and contains a fairly extensive system of small lakes in the headwaters, its yield tends to be fairly low and is not synchronized with the runoff from the Athabasca River basin. Consequently, the flow in the Clearwater River during the breakup of the Athabasca River ice cover does not usually contribute significantly to the ice jamming problems at Fort McMurray.

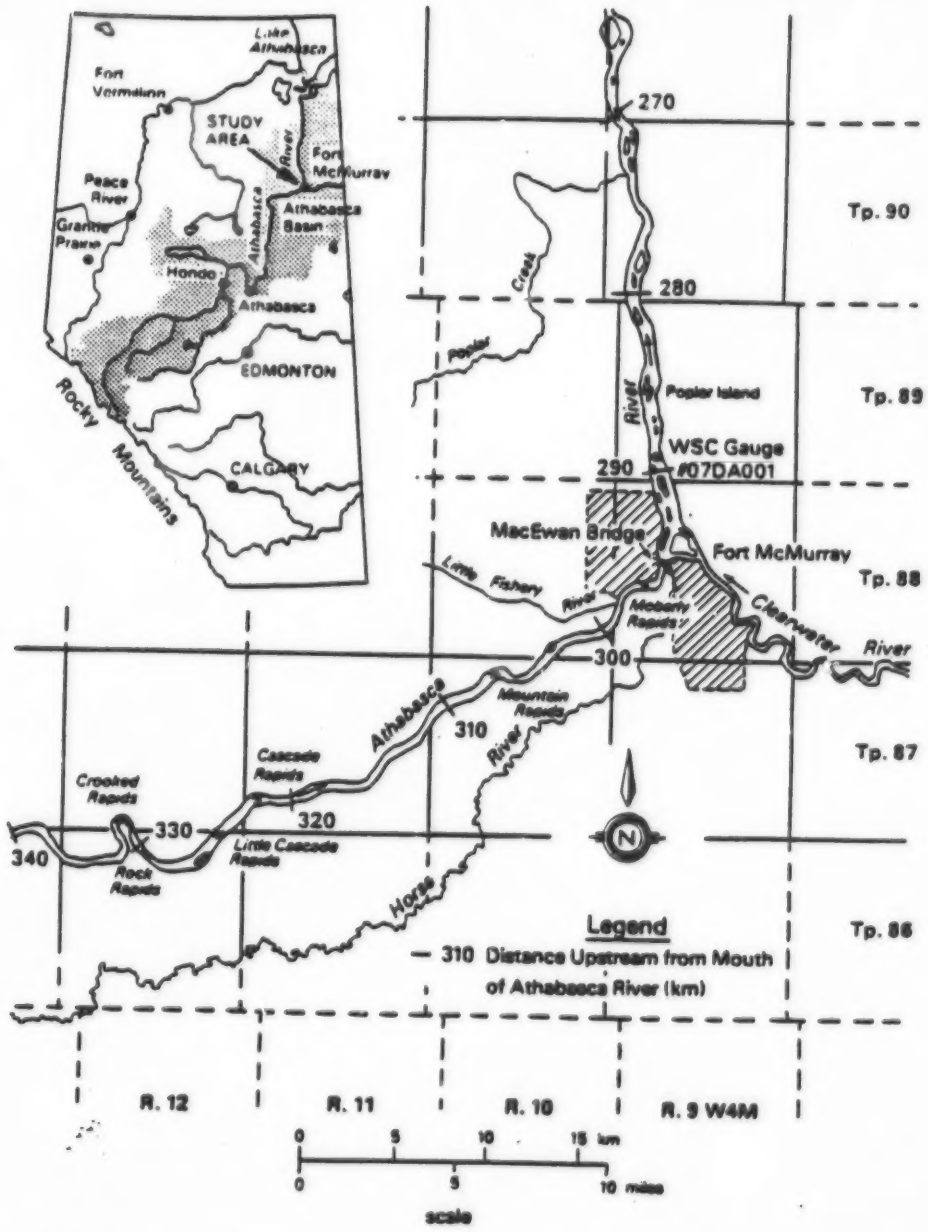


Figure 1 Study area.

2.2 Reach Description

For about 140 km upstream of the Fort McMurray, the Athabasca River is deeply entrenched in a narrow meandering valley and drops through a series of rapids (figure 2). The average width of the river channel is about 450 m. Channel bed material in the long, relatively low velocity stretches between the rapids, is mainly gravel and cobbles.

At Fort McMurray, the characteristics of the river change rather abruptly. The channel straightens, the slope decreases, and the width increases to about 750 m. The channel also contains numerous islands and mid-channel bars. These bars consist of a mixture of sand and gravel, the finer fractions of which reflect the sediment supplied from the Clearwater River. Recent open water level data collected by the Alberta Research Council indicates that the water surface slope change occurs between Parsons Creek and Poplar Island, approximately 2.5 km downstream of the WSC gauge (07DA001). Average, gradients determined from profiles shown in figure 7 (see section 4.3.2) are summarized in table 1.

Table 1 Water surface slopes of the Athabasca River in the vicinity of Fort McMurray

Reach	River Distance (km)	Average Slope (m/m)
Little Fishery River to Parsons Creek	298.6 - 287.1	0.00047
Parsons Creek to Suncor Oil Sands Development	287.1 - 270.7	0.00017

Note that the slope of 0.00047 immediately upstream of Parsons Creek in the vicinity of the WSC gauge is more than double the values quoted by both Andres and Rickert (1984, 1985a, 1985b) and Kellerhals, Neill and Bray (1972). Uniform flow computations based on surveyed water surface profiles for low flow conditions indicate that the Manning roughness coefficient is about 0.025.

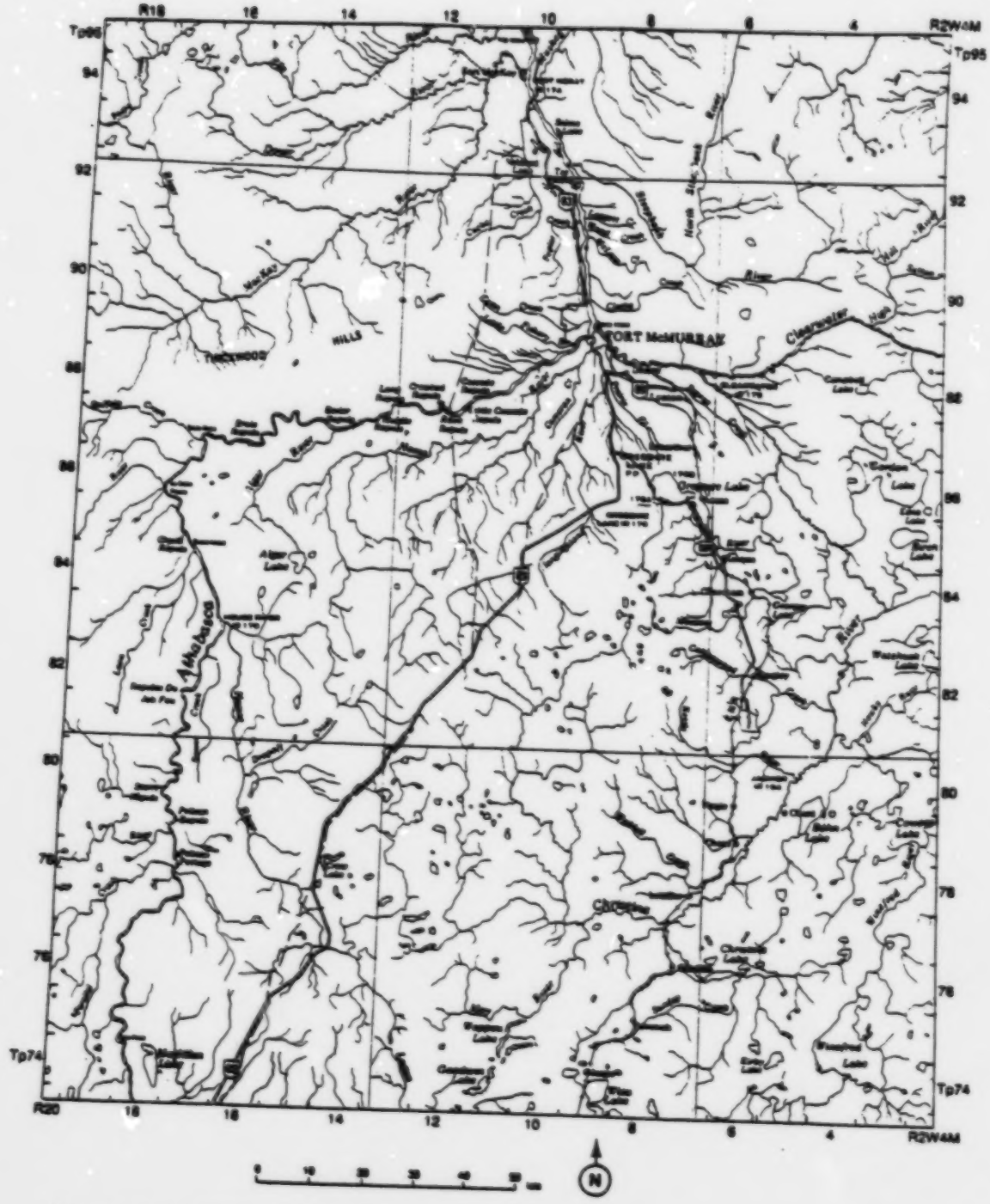


Figure 2 Channel planform and location of rapids upstream of Fort McMurray.

2.3 Breakup Processes

Previous observations have shown that the timing of breakup along the Athabasca River does not necessarily coincide with the usual warming trend in the southernmost part of the basin. Very often the rapids sections above Fort McMurray are cleared of ice prior to the main spring runoff event. It appears that due to the steep slopes and associated high flow velocities in these areas, a small increase in discharge can trigger the breakup process without significant deterioration of the ice cover.

Once breakup has been initiated, the basic processes of ice cover destruction and ice jam formation appears to be somewhat similar from year to year. Small ice packs move from the rapid sections downstream into lower velocity areas with a more competent solid ice cover. The ice floes accumulate at the front of these ice-covered stretches and small jams develop. As the discharge increases and the solid ice cover in these areas weakens by thermal effects, the smaller jams move downstream, grow in size and alternately jam, build and move again. By the time the ice run reaches Crooked Rapids, approximately 45 km upstream of Fort McMurray, most of the smaller jams are usually transformed into a single large accumulation which often exceeds 25 km in length and produces a stage increase in the order of 8 to 12 m above normal open water levels (Andres and Doyle, 1984).

Once the ice run reaches Fort McMurray, it usually decelerates due to both the presence of the numerous bars and islands and the sharp reduction in channel slope. Another factor which also contributes to the sudden jamming and associated rise in water level is the more competent downstream ice cover that tends to prevail because of lower air temperatures in this more northerly part of the basin (Andres, 1980).

Most jams in the Fort McMurray area tend to remain in place if the incoming flows are steady or decrease following the formation of the jam. Only after about 3 to 7 days is the ice removed by thermal erosion. Occasionally the ice jams are destroyed by surges from upstream if jam

formation is quickly followed by an increase in river discharge from snowmelt inflow from upstream.

2.4 Previous Floods During Spring Breakup

The most severe documented jam at Fort McMurray occurred in 1875 and produced a water level at the Clearwater River confluence of about 252 m. or some 7 m above bankfull stage (Blench, 1964). Overbank flooding is also known to have occurred on at least nine other occasions since that year.

The worst recent flooding in the city was in April, 1977, when the stage at the mouth of the Clearwater River rose to a level of about 247.5 m. A similar jam occurred in 1979. However, the peak stage at the confluence during this event was about 0.8 m lower than in 1977 and thus there was less damage in the city. In 1978, a major jam formed at MacEwan Bridge, approximately 2 km upstream of the confluence. The resulting peak water levels were higher than those observed in 1977 but because of the much higher banks along the river above the bridge, no flooding was experienced. Water surface profiles measured during these recent events are given by Andres and Doyle (1984). Since 1979, breakup on the Athabasca River has been relatively mild and consequently, somewhat uneventful for the residents of Fort McMurray.

3.0 EQUILIBRIUM ICE JAM THEORIES

The classical paper describing the hydromechanics of river ice jams was presented by Pariset and Hausser (1961) and this was enlarged upon by Pariset, et al. (1966). The early work of Michel (1971) essentially parallels that of Pariset and Hausser. Uzuner and Kennedy's (1974) ice jam formulation was shown by Beltaos (1978) to be identical with Pariset, et al. (1966) at the position of equilibrium ice jam thickness. Beltaos (1983) has also expressed the equilibrium ice jam thickness in terms of dimensionless independent parameters of stage and discharge, respectively.

Using a simple force balance analysis for a typical floating ice cover in a rectangular channel, Pariset, et al. (1966) classified rivers as being either "wide" or "narrow". In a "wide" channel, the streamwise thrust increases initially downstream of the ice front and remains constant after reaching a limiting value. The cover thickens through successive shoves until its internal resistance is equal to the sum of the external forces. For "narrow" channels, the streamwise thrust on the cover is greatest at the leading edge. In this case, jams form by submergence of ice floes under the front. Shoving, or internal collapse of the cover, does not occur.

In the Fort McMurray area, both modes of ice cover formation have been observed (Andres and Rickert, 1985a, 1985b). However the dominant process during spring breakup is clearly the internal collapse and thickening of the cover by shoving (i.e. "wide" channel jams). Jam formation by submergence of ice floes results mostly from low speed, low ice concentration runs and only occurs in certain reaches during freeze-up.

3.1 Equilibrium Ice Jam Thickness

The expression given by Pariset, et al. (1966) for the equilibrium thickness of a "wide" channel jam is

$$[1] \qquad \mu\rho_i(1-s_i)gt^2/2 + C_i t = [W(\tau_i + \rho_i gSt)/2]$$

where μ is the dimensionless coefficient related to the internal friction of the ice cover, ρ_i is the density of the ice, s_i is the specific gravity of ice, t is the jam thickness, W is the channel width, τ_i is the shear on the underside of the ice cover, g is the acceleration of gravity, S is the water surface slope and C_i is the cohesion of the ice cover.

As pointed out by Beltaos (1978), the relation for the equilibrium thickness derived by Uzuner and Kennedy (1974) can be shown to have the same form as equation [1]. In this equation, the terms on the right-hand side describe the external or driving forces on the cover; the first being the shear exerted by the flowing water and the second being the streamwise component of the cover weight. The terms on the left-hand side describe the resistance due to internal friction and cohesion, respectively. For spring breakup jams, the cohesion term is usually neglected. Assuming that the porosity of the cover is the same both above and below the water level, the maximum (equilibrium) stage, H, of a floating jam is

$$[2] \qquad H = h + s_i t$$

where h is the depth of flow beneath the cover. This depth can also be divided into two components, R_i for the ice and R_b for the bed as shown on figure 3. In other words

$$[3] \qquad h = R_i + R_b$$

Note that $h=2R_o$ where R_o is the hydraulic radius of an ice-covered channel. The shear stress, τ_i, which appears in equation [1] is

$$[4] \qquad \tau_i = \rho g S R_i$$

where ρ is the density of water. Substituting equation [4] into equation [1] and rearranging, gives (Beltaos, 1978)

$$[5] \qquad \mu = [SW/t(1+R_i/s_i t)-2C_i/s_i \rho g t]/(1-s_i)$$

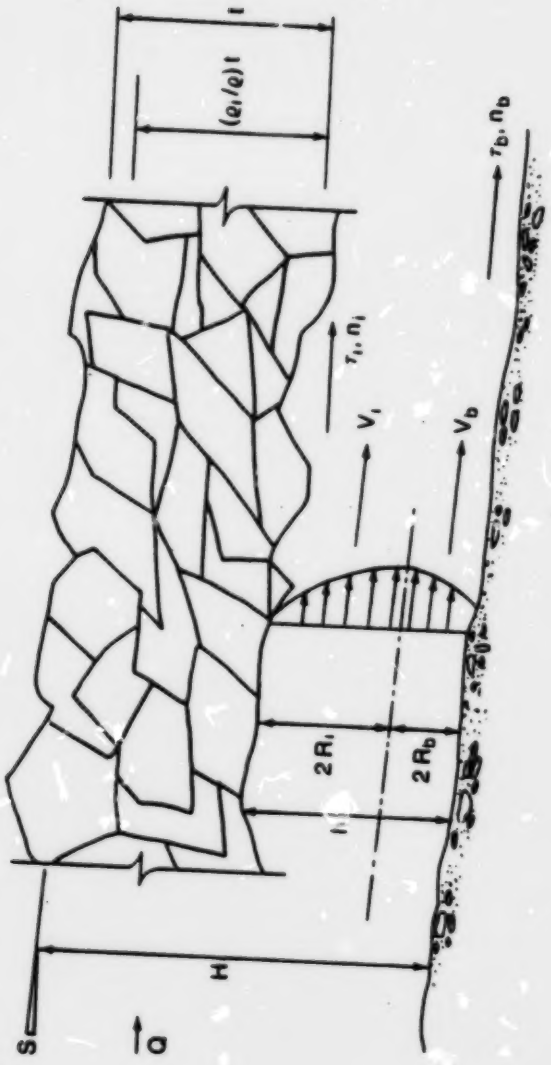


Figure 3 Definition sketch for an equilibrium ice jam.

For s_i=0.92, ρ=1000 kg/m3, g=9.81 m/s2 and C_i=0, equation [5] can be simplified to

[6] $$\mu = 12.5(SW/t)\ (1+R_i/0.92t)$$

with t expressed in metres.

3.2 Uniform Flow in an Ice-Covered Channel

Uniform flow beneath the equilibrium section of an ice jam is most often described by the Manning equation

[7] $$Q = AR_o^{2/3}S^{1/2}/n_o$$

where A is the cross-sectional area, R_o is the hydraulic radius, S is the water surface slope, and n_o is the composite Manning roughness coefficient. The hydraulic radius under an ice cover can be approximated as one-half of the depth of flow and equation [7] can be simplified to

[8] $$Q = 0.63\ Wh^{5/3}S^{1/2}/n_o$$

and from equation [2]

[9] $$Q = 0.63\ W(H-0.92t)^{5/3}S^{1/2}/n_o$$

The overall composite roughness can be computed by, the well-known Sabaneev equation (Michel, 1971; Calkins, 1983). Such that

[10] $$n_o = [(n_i^{3/2} + n_b^{3/2})/2]^{2/3}$$

where n_i and n_b are the Manning roughness coefficients for the ice cover and riverbed, respectively.

According to Beltaos (1978), there is some laboratory and theoretical support for the assumption of equal average velocities in the

ice and bed-controlled portions of the channel (see figure 3) and he has shown that

$$[11] \qquad R_i/R_b = (n_i/n_b)^{3/2}$$

Use of equation [11] is justified by a lack of reliable field measurements from which to further define better approximations.

3.3 Indirect Determinations of Ice Jam Thickness

Application of the preceeding set of equations is hampered by lack of safe, reliable methods of measuring ice jam thicknesses during spring breakup. It has been suggested by Calkins (1983) that the height of the vertical shear walls usually found along the banks after jam release may be representative of the average thickness. However, such measurements can also be extremely difficult to obtain, particularly along relatively deep channels where a large portion of the shear walls may still be deeply submerged.

Typically, the known or measurable parameters are Q, H, W, S and the open-water Manning bed roughness coefficient, n_b. Variations of n_b with river stage is a secondary refinement which is probably not justified for the level of analysis described herein. The unknown parameters are seven (t, t_i, R_i, R_b, n_o, n_i, and μ) while the number of available equations is six (i.e. equations 2, 3, 6, 9, 10 and 11). Obviously a solution is not possible unless another relationship is introduced to close the system.

To obtain an other equation and thus effect closure, Beltaos (1978, 1983) suggested that the ice cover roughness, n_i, could be estimated from

$$[12] \qquad n_i = 0.072t^{0.40}/R_i^{0.23}$$

The above equation was developed from the roughness data of Nezhikovskiy (1964) for accumulations of ice floes during freeze-up. Evidence to support this jam thickness-roughness relation was found from

the laboratory investigations of Tatinclaux and Cheng (1978) and Calkins and Muller (1980) and a somewhat similar relation for log jams derived by Kennedy (1958) from both laboratory and field measurements. Another approach that has been utilized in the past is to fix either the ratio n_i/n_b (Pariset, et al., 1966; Calkins, 1983) or the ratio t/H (Michel, 1980).

However, according to Beltaos (1983), neither of these approaches nor equation [12] can be considered truly satisfactory. Nezhikhovskiy's data has not been verified by field measurements elsewhere. Fixing the ratio n_i/n_b is purely arbitrary with no evidence of an universal value, while fixing the ratio t/H is based on theoretical considerations which have also never been tested against field data. However, because it is based on actual field measurements, equation [12] was considered by Beltaos to be the least objectionable at the present time.

Andres (1980) questioned the use of equation [12] on the grounds that n_i was probably more dependent on the size of the ice floes and their arrangement within the jam than on its thickness. He suggested that in cases where a jam remains in place during a period of changing discharge and at least two sets of stage-discharge measurements are available, then the thickness of the jam can be determined directly from

$$[13] \qquad Q_1/Q_2 = [(H_1 - 0.92t)/(H_2 - 0.92t)]^{5/3}$$

where the subscripts 1 and 2 represent successive measurements during the same jam.

Equation [13] is based on the Manning flow equation [9] and assumes that both the jam thickness and roughness do not change appreciably following establishment of the equilibrium section. In other words, thermal erosion of the underside of the jam is minor and the change in stage is mainly due to fluctuations in discharge.

In practice, the approach proposed by Andres (1980) seems reasonable as long as the time between the peak formative discharge (during the ice

run) and the second known discharge is not too great. However, in the case of the Athabasca River at Fort McMurray, application of this method can also become fairly complicated. Discharge estimates downstream of the jam tend to be unreliable because of rapidly changing roughnesses due to the deterioration of ice cover. Also there is some difficulty in transferring discharge data from a convenient measurement point downstream of the jam due to the unsteady nature of the discharge. Consequently, there is always an element of subjectivity associated with discharge estimates required for the application of this technique.

4.0 SPRING BREAKUP AT FORT MCMURRAY, 1986

In mid-April of 1986, an aerial and ground reconnaissance program was carried out to gather information on ice conditions during breakup along the Athabasca River between the Pembina River and Fort McMurray. The observations contained in this report are principally focussed on the ice movement and subsequent jamming that took place in the Fort McMurray area. Breakup in the upper reaches of the river is described in detail by Andres (1988) and is not repeated here.

The toe of the 1986 jam was located near the mouth of Parsons Creek, approximately 7 km downstream of MacEwan bridge. During jam formation on April 19, the physical characteristics of the moving ice front and water levels at the bridge were recorded. Once the jam had stabilized on April 20, peak ice levels between Mountain Rapids and the Suncor Oil Sands Development were determined by ground surveys at accessible points with established benchmarks and by oblique photographs taken from the air at the various targets placed along the river specifically for this purpose (see Andres and Rickert, 1984). These ground stations are located at Suncor, the Sawmill, the waste water treatment plant, the mouth of the Clearwater River, MacEwan Bridge and a pipeline crossing near Moberly Rapids. Water level information was also obtained at the accessible ground stations on April 21 and 22.

The following discussion begins with a brief overview of meteorological and river ice conditions in the area prior to breakup. This is followed by a summary of the observed ice movement and water level fluctuations during breakup, a description of the physical characteristics of the jam and finally, an evaluation of the flows in the river during jam formation, the roughness of the jam and its coefficient of internal friction. The analysis was based on the theory described in the preceeding section of this report.

4.1 Pre-Breakup Meteorological and River Ice Conditions

Air temperature and precipitation records for Fort McMurray during the winter of 1985-86 are summarized on table 2. November was the coldest month with an average daily temperature of -16.3°C or 8.1°C below normal for the month. The months of December, January and March, on the other hand, were unusually mild. Average daily temperatures were 4.2°C, 10.0°C and 6.1°C higher than normal, respectively.

November through March precipitation at Fort McMurray was well below normal at 92.7 mm. Of this total, approximately 70 percent fell during December and January. Precipitation in February was particularly light, being only about 26 percent of the long-term average for the month.

Pre-breakup ice thickness measurements made by WSC and the ARC are summarized on tables 3 and 4, respectively. These indicate that the submerged thickness of the cover was about 1.0 m by early January and then remained fairly constant thereafter. Compared to previous years (see Andres and Rickert, 1984, 1985a, 1985b), the early January ice cover was the thickest on record by about 0.2 to 0.3 m which suggests that rather large volumes of frazil ice may have been generated during the unusually cold freeze-up period in November.

The WSC discharge measurements are also summarized on table 3 and show that contrary to the previous years, no appreciable smoothing of the ice cover bottom took place between early January and mid-April. The overall Manning roughness coefficient was 0.028 on all three survey dates. Assuming a bed roughness of 0.025 (see Section 2.2), the corresponding roughness of the ice cover was about 0.031.

4.2 Breakup Observations

Aerial observations indicate that breakup of the ice cover between the town of Athabasca and the city of Fort McMurray occurred on April 19 and that the toe of the moving ice passed Brule Point (km 396) at about

Table 2 Monthly air temperatures and precipitation at Fort McMurray for the winter of 1985-86

	Month				
	November	December	January	February	March
Average Maximum Daily Temperature (°C)	-12.1 (-3.6)	-7.8 (-12.2)	-7.5 (-16.5)	-8.7 (-9.0)	2.8 (-2.2)
Average Minimum Daily Temperature (°C)	-20.5 (-12.7)	-17.8 (-21.7)	-16.0 (-27.1)	-20.9 (-21.8)	-9.0 (-16.1)
Average Minimum Daily Temperature (°C)	-16.3 (-8.2)	-12.8 (-17.0)	-11.8 (-21.8)	-14.8 (-15.4)	-3.1 (-9.2)
Total Precipitation (mm)	10.2 (25.2)	30.9 (25.0)	34.4 (22.7)	5.0 (18.8)	12.2 (20.7)

Note: Bracketed values indicate long-term normal.
Total precipitation is the water equivalent.

Table 3 Hydraulic characteristics of the Athabasca River near Fort McMurray during the winter of 1985-86

Parameter	Date		
	January 9*	March 7*	April 15**
Discharge, Q(m3/s)	176	166	391
Flow Area, A(m2)	265	252	587
Top Width, W(m)	170	166	370
Hydraulic Radius, R_o(m)	.078	0.76	0.79
Ice Thickness, t(m)			
- minimum	0.70	0.85	0.85
- maximum	1.25	1.40	1.35
- average[1]	1.02	1.04	1.03
Water Surface Slope[2], S(m/km)	0.47	0.47	0.47
Composite Roughness, n_o	.028	.028	.028
Ice Cover Roughness[3], n_i	.031	.031	.031

Note: *Measurement made by WSC at or near gauge 07DA001
**Measurement made by WSC above MacEwan Bridge.
[1]Cross-sectionally averaged value
[2]Based on ARC open water profile
[3]Computed by the Sabaneev equation with a bed roughness, n_b, of 0.025.

10:00 hours. The front was later observed at MacEwan Bridge, approximately 100 km downstream of Brule Point, at about 21:00 hours. Assuming that the ice run was continuous between these two points, its celerity would have been about 12.5 km/hr or 3.5 m/s.

Observations at the bridge indicated the larger individual ice floes during the run varied in thickness from 0.8 m to 1.5 m and occasionally exceeded 4 m in diameter. At 21:06 hours, this ice was moving at a rate of about 4.3 m/s (figure 4). By 21:23 hours, the surface velocity had increased to 7.4 m/s. However by the time that the last velocity measurement was made at 22:03 hours, the ice had slowed to 5.5 m/s. The actual time at which all movement ceased at the bridge is not known because of darkness but probably occurred very early in the morning of April 20.

Table 4 Ice thickness measurements[1], April 1 and 2, 1986

Location[1] (km)	Ice Thickness (m)
296.9	1.20
296.4	1.11
295.9	1.17
295.4*	0.96*
294.4	1.16
293.9	0.99
293.4	1.10
292.2**	0.92**
292.4**	1.13**
291.9*	0.78*
Mean	1.05
Standard Deviation	0.13

Note: [1]MacEwan Bridge located at km 294.9
*Primarily thermal ice
**High percentage of snow ice

The water levels recorded by the Alberta Research Council at the bridge and by Water Survey of Canada at the gauging station below Fort McMurray (07DA001) are shown on figures 4 and 5, respectively. It would appear that the toe of the moving ice took about 1 hour to travel the 5 km distance between the two points. This corresponds to a celerity of only 1.4 m/s, which is considerably less than appears to have occurred between Brule Point and MacEwan Bridge.

As indicated on figure 5, the water level at the gauge was fairly steady at 239.0 m for about 3 days prior to breakup. During the ice run past the gauge, which began at about 22:00 hours on April 19, there was a stage increase of 1.8 m. The water level remained at 240.8 m until 11:00 hours on April 20 and then gradually dropped to 240.3 m by 02:00 hours on April 22. Between 02:00 and 14:00 hours on April 22, the gauge level increased by about 0.3 m. The stage then remained relatively steady at 240.6 m until the jam finally released at about 16:00 hours on April 24. The drop in water level during the 5 hour period following jam release was about 2.5 m.

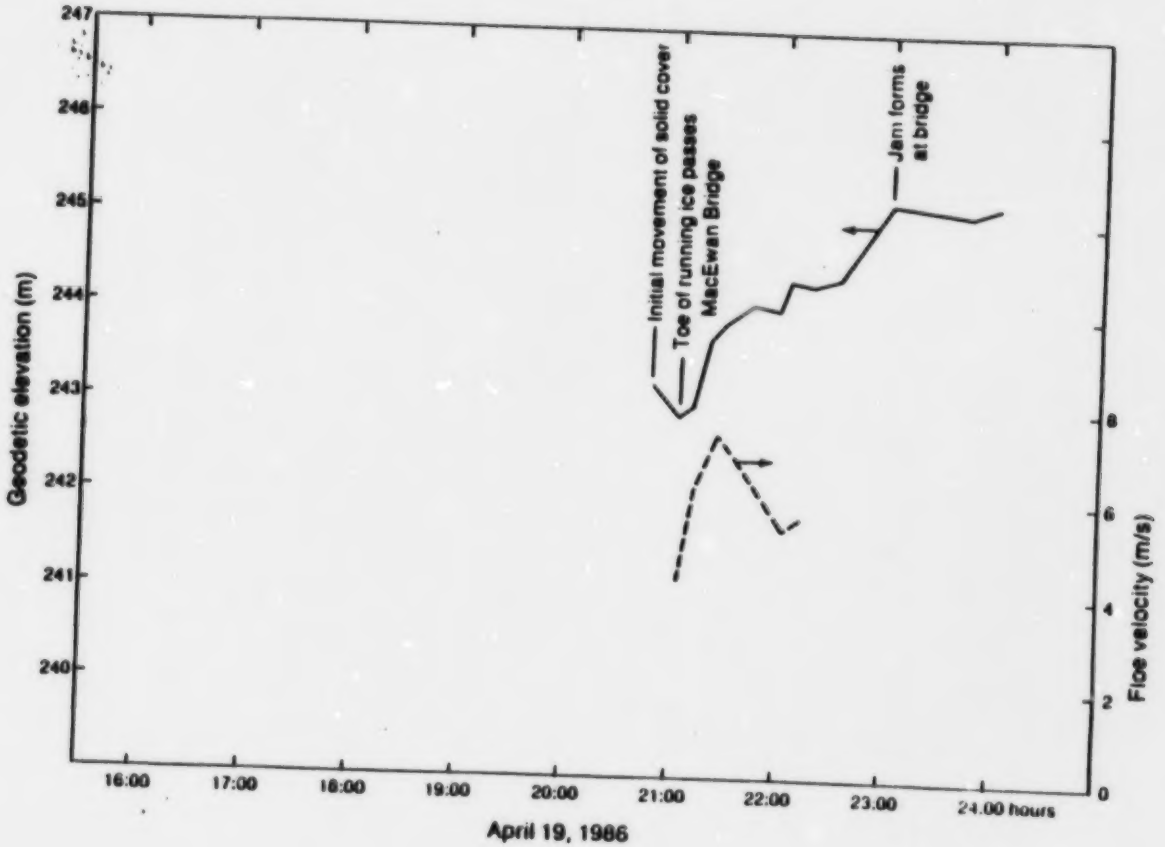


Figure 4 Velocity and stage fluctuations during the ice run past MacEwan Bridge, April 1986.

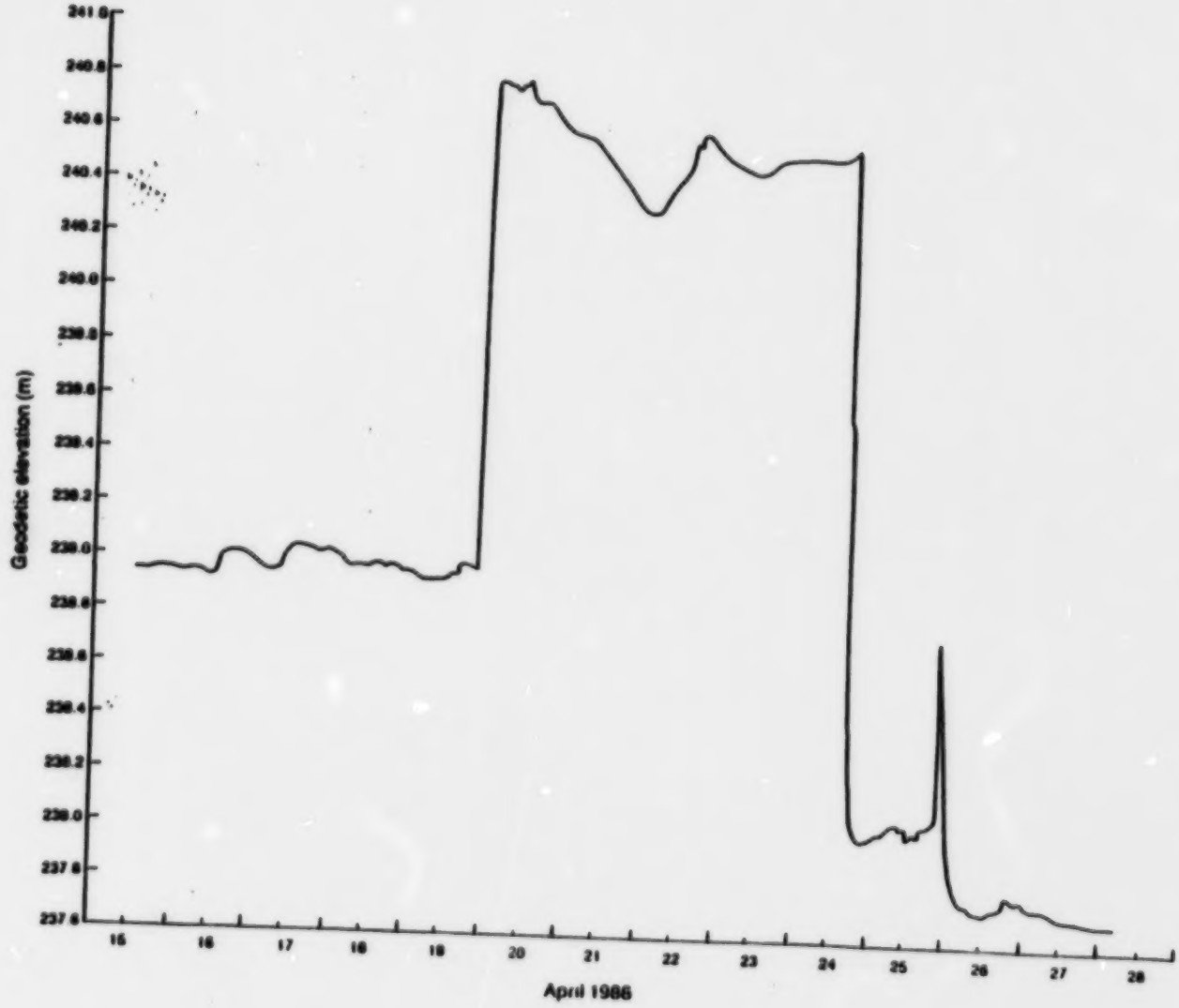


Figure 5 Water Levels at the WSC Gauge #07DA001 during breakup on the Athabasca River, April 1986.

4.3 Jam Documentation

4.3.1 Physical Characteristics

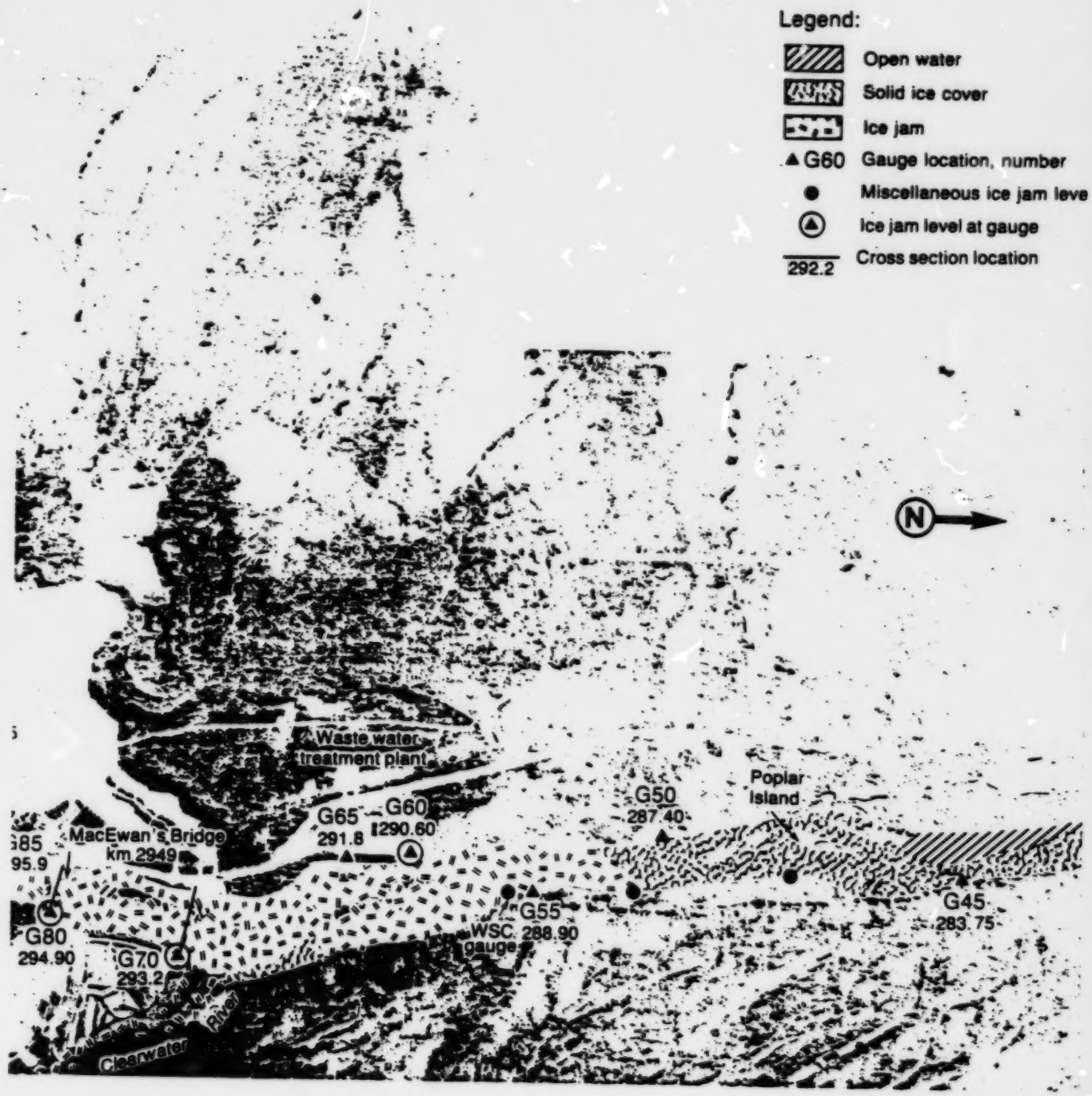
The areal extent of the jam and the surveyed jam profiles (maximum ice levels and April 20 water surface elevations) are shown on figures 6 and 7, respectively. Typical cross section within the equilibrium section of jam are shown in figure 8. The toe (figure 9) was situated at km 288, approximately 0.8 km upstream of the mouth of Parsons Creek. The cover was consolidated and the jam was in equilibrium at the mouth of the Clearwater River (figure 10) into which some of the Athabasca River ice had been pushed. At MacEwan Bridge the cover was also consolidated and extremely rough (figure 11). The head of the jam (figure 12) was located at km 304, approximately 3 km downstream of Mountain Rapids. The average water surface slope through the toe area (km 288 to km 293) appears from the profile to have been about 0.0010 m/m. The equilibrium portion of the jam (the only part amenable to simple analysis) appears to have extended from km 293 (Clearwater River confluence) to km 304 and had an average slope of 0.00047 m/m. This is the same as the open water surface slope measured in August, 1986.

Available channel cross-section information indicates that the average width and height through the equilibrium portion of the jam were about 350 m and 6.5 m, respectively. Compared to other recent jams in the Fort McMurray area as reported by Andres and Doyle (1984), the average jam height in 1986 was about 2.0 m lower than observed in 1977 and 1978 and about 1.0 m lower than in 1979.

4.3.2 Discharge Estimates

The flows in the Athabasca River during the jam are not known precisely even though the WSC gauging station below Fort McMurray remained operative throughout the entire event. One reason for the uncertainty is that no stage discharge relation for the gauge can adequately account for the changing channel roughness and ice thickness during ice movements. The other reason is that the gauge was situated in the downstream toe or

Athabasca River
Beginning of observation
Mountain Rapids
G115
307.06
G110
303.75
G105
300.75
G100
298.7
G95
297
G90
296
Horse River
Moberly Rapids
Fort McMurray


Legend:
Open water
Solid ice cover
Ice jam
▲G60 Gauge location, number
Miscellaneous ice jam leve
Ice jam level at gauge
292.2 Cross section location
N
Waste water treatment plant
G65
291.8
G60
290.60
G50
287.40
Poplar Island
MacEwan's Bridge
km 2949
G85
95.9
G80
294.90
G70
293.2
G55
WSC gauge
288.90
G45
283.75
Clearwater River

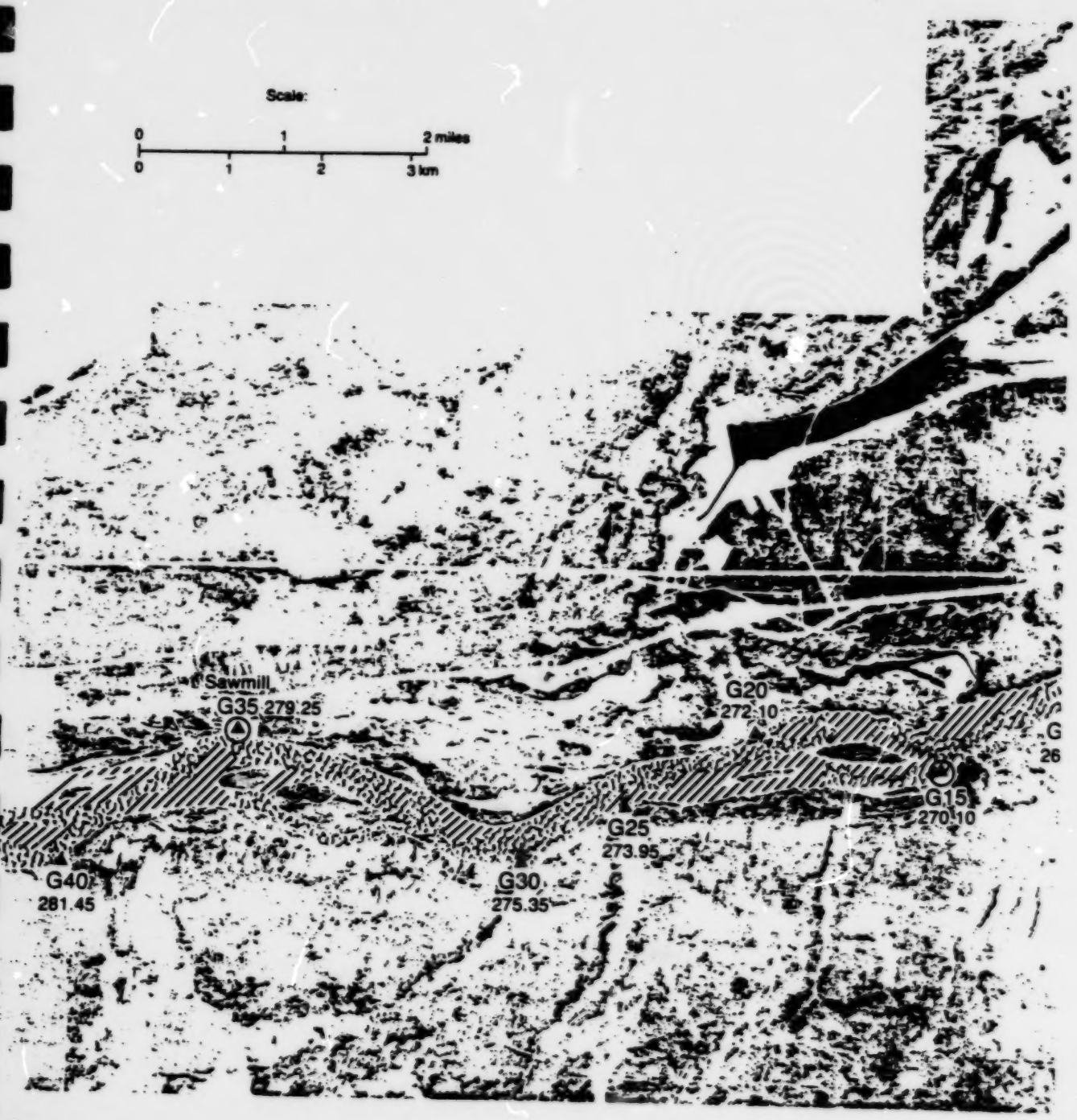

Scale:
0
1
2 miles
0
1
2
3 km
Sawmill
G35 279.25
G20
272.10
G
26
G15
270.10
G25
273.95
G40
281.45
G30
275.35

Figure 6. Configuration of the stable ice jam, April 19 and 20, 1986.

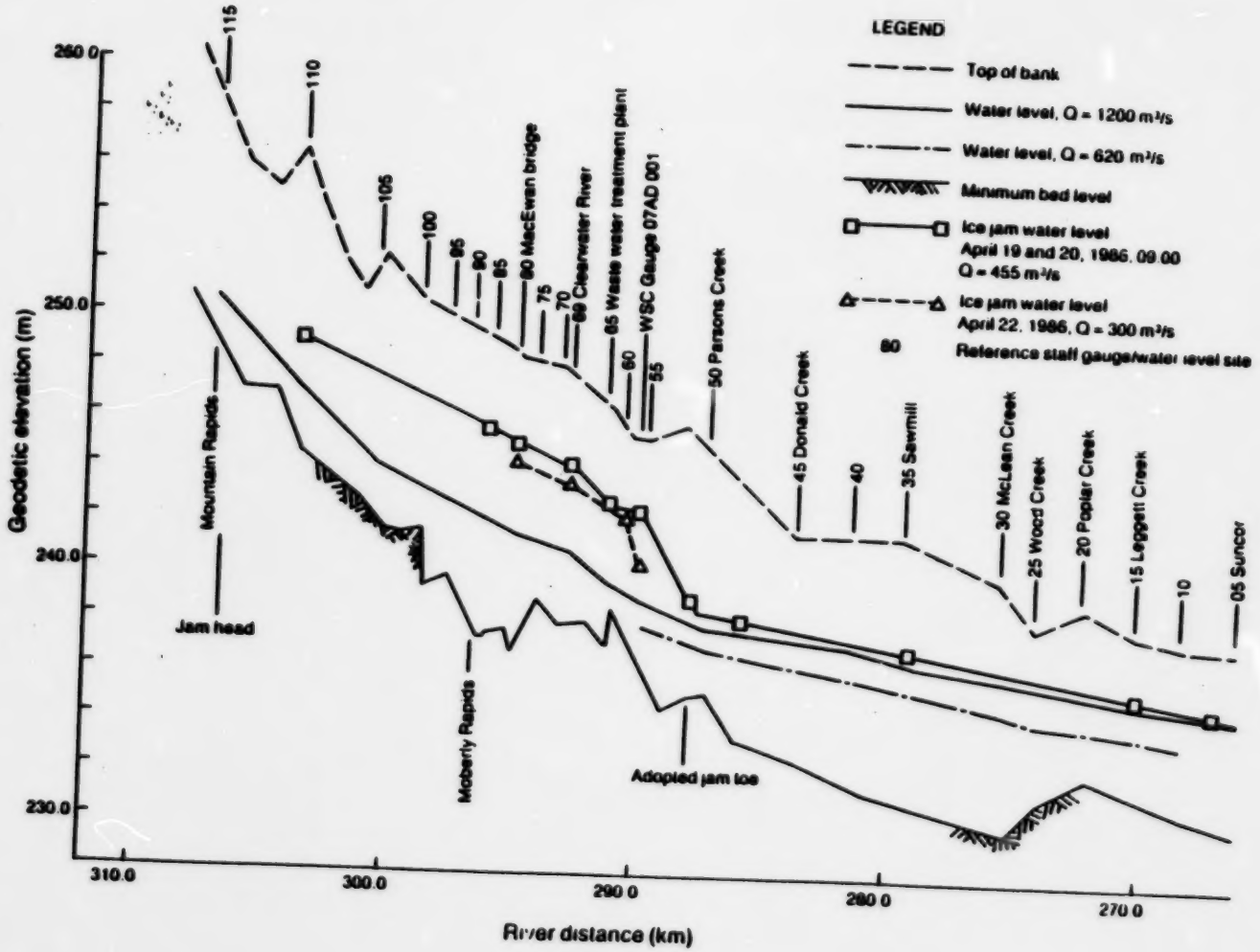
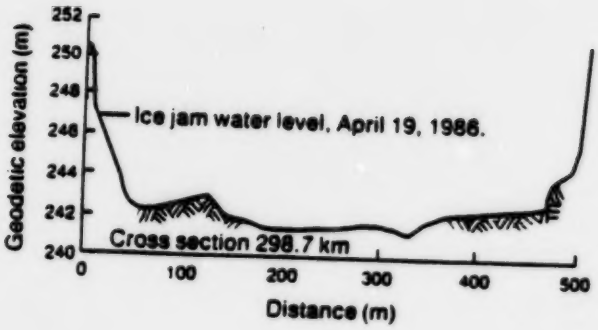
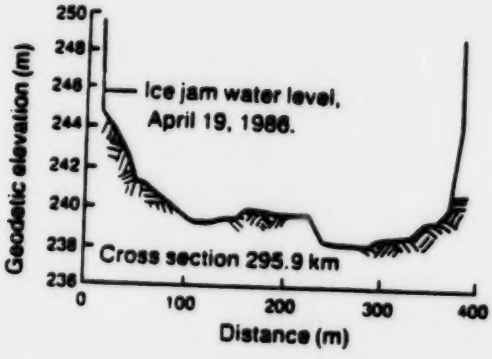
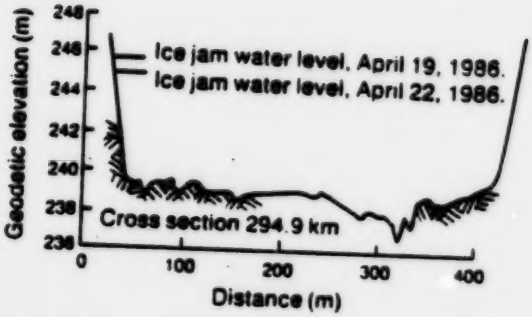


Figure 7 Ice jam profile, April 19 & 20, 1986.







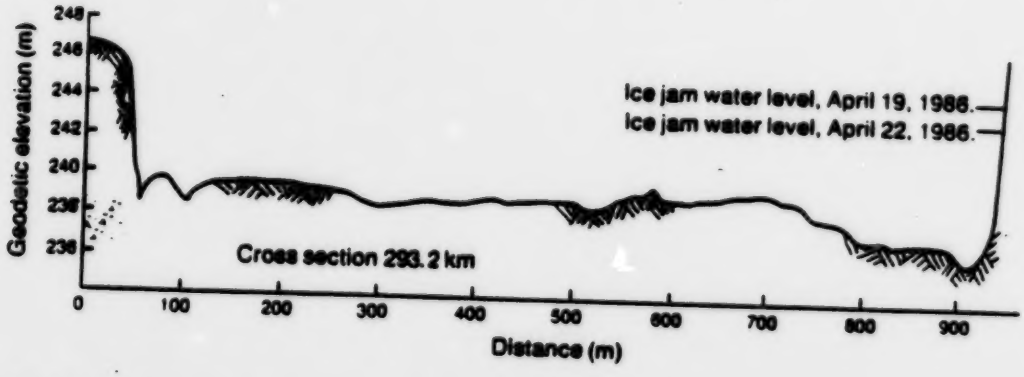


Figure 8 Surveyed cross sections within the equilibrium portion of the 1986 jam.

Figure 9 Toe of the equilibrium ice jam, April 21, 1986; looking upstream towards the mouth of the Clearwater River.

Figure 10 Configuration of the ice jam at the mouth of the Clearwater River April 21, 1986; looking downstream.

Figure 11 Surface appearance of the ice jam at MacEwan Bridge, April 21, 1986.

Figure 12 Head of the equilibrium ice jam, April 21, 1986; looking downstream from below Mountain Rapids.

transition region where the flow is highly non-uniform and cannot be analyzed according to conventional theory.

However, in 1986, several water level measurements were made along the river below the toe of the jam. These measurements, together with reach-averaged channel properties determined from previously surveyed cross-sections between km 286 and km 268, enabled calculation of both the formative discharge on April 20 and the prevailing discharge once the jam had stabilized and river levels had decreased on April 22. The flow computations were based on equation [7] and assume that the thickness and roughness of the ice cover below the jam were essentially the same as those determined from the WSC discharge measurement shortly before breakup (see table 2). The results indicate that the discharge below Fort McMurray on the above dates were approximately 540 m3/s and 390 m3/s, respectively. Allowing for inflow from the Clearwater River, the estimated flows in the equilibrium portion of the jam above the confluence are 455 m3/s on April 20 and 300 m3/s on April 22. In contrast, the WSC estimates on these dates are about 410 m3/s and 470 m3/s, respectively if the same Clearwater River inflow (90 m3/s) is used.

It should be noted that during jam formation April 19/20, several small open water leads developed along the river below the jam (see figure 6). However available channel cross-sections clearly indicate that virtually all of these leads were located in very shallow, low-velocity areas adjacent to the banks. Since there was probably little or no effective flow in these areas, there is no reason to believe that the computations outlined previously are unrealistic.

4.3.3. Hydraulic Characteristics

As noted previously, the jam near Parsons Creek remained in place long enough for jam heights to be determined at two greatly different discharges (i.e. 455 m3/s on April 20 and 300 m3/s on April 22). By assuming that no appreciable changes in jam thickness roughness occurred during the two-day period and that the change in stage resulted from the

change in discharge, it was possible to independently determine the thickness t using equation [13] as suggested by Andres (1980). With the known value of t, equations [2], [3], [6], [9], [10] and [11] were then used to solve for the other hydraulic parameters which characterize the observed jam at the formative discharge of 455 m3/s.

The results of the computations are summarized on table 5. The estimated thickness of 3.6 m is slightly lower than was determined by Andres and Doyle (1984) for the jams in 1977, 1978 and 1979 but considering the relatively low formative discharge, appears to be reasonable. The composite roughness, n_o and internal friction coefficient, μ were found to be 0.074 and 1.1, respectively. Both of these values are consistent with previous finding for the other jams.

If the Beltaos (1978, 1983) rather than the Andres (1980) approach is used to estimate the jam thickness, the results for this particular case are not significantly different. A trial and error solution of equation [12] gives a computed thickness of 3.8 m. The corresponding values of n_o and μ are 0.067 and 1.0, respectively.

Table 5 Summary of measured and computed ice jam characteristics, 1986

Formative Discharge, Q(m3/s)	455
Slope, S(m/m)	0.00047
Width, W(m)	350
Jam Height, H(m)	6.5
Jam Thickness, t(m)	3.6
Composite Roughness, n_o	0.074
Bed Roughness, n_b	0.025
Ice Cover Roughness, n_i	0.109
Hydraulic Radius (Bed), R_b(m)	0.3
Hydraulic Radius (Ice), R_i(m)	2.9
Coefficient of Internal Friction, μ	1.1

Note: Equilibrium section of jam between km 293 and km 304

5.0 SPRING BREAKUP AT FORT MCMURRAY, 1987

In mid-April of 1987 the annual aerial and ground reconnaissance program was carried out to gather information on ice conditions during breakup on the Athabasca River. The observations contained herein focus on the breakup and subsequent jamming that took place in the vicinity of Fort McMurray. Breakup in the upper reaches is described in detail by Andres and Mostert (1989) and is not included here.

The following discussion begins with a brief overview of the meteorological and river ice conditions in the area prior to breakup. This is followed by a description of the winter ice roughness and thickness and a summary of the observed ice movements and subsequent water level fluctuations during breakup. A stable jam had formed in the vicinity of Fort McMurray and water levels in the reach of interest were sufficiently high to warrant concern. These water levels and the subsequent destruction and downstream movement of the jam are addressed. Unfortunately, good estimates of the formative discharge could not be made and hence the stability analysis could not be carried out.

5.1 Pre-breakup Meteorological and River Ice Conditions

Air temperature and precipitation records for the Fort McMurray region for the winter of 1986-87 are summarized on table 6. As in the previous year, November was again the coldest month, with an average daily temperature of -13.6°C or 5.4°C below normal. The months of December, January and February were unusually mild. The average daily temperatures were 8.6°C, 12.6°C, and 8.0°C higher than normal, respectively. March had a near normal mean temperature.

The total precipitation for the November to March period was 132 mm or about 20 mm or 18% above normal. The month of November had significantly more precipitation than normal while December was well below normal and January was slightly below normal. The months of February and March had substantially more (60% and 81%, respectively) precipitation than normal.

Table 6 Monthly air temperatures and precipitation at Fort McMurray for the winter of 1986-87

	Month				
	November	December	January	February	March
Average Maximum Daily Temperature (°C)	-8.6 (-3.5)	-3.4 (-12.2)	-4.4 (-16.5)	-2.5 (-9.0)	-2.7 (-2.2)
Average Minimum Daily Temperature (°C)	-18.5 (-12.7)	-13.3 (-21.7)	-13.9 (-27.1)	-12.3 (-21.8)	-14.1 (-16.1)
Average Mean Daily Temperature (°C)	-13.6 (-8.2)	-8.4 (-17.0)	-9.2 (-21.8)	-7.4 (-15.4)	-8.4 (-9.2)
Total Precipitation (mm)	32.4 (25.5)	11.8 (25.0)	20.4 (22.7)	30.0 (18.8)	37.4 (20.7)

Note: Bracketed values indicate long-term normals.

Pre-breakup ice thickness measurements reported by WSC are summarized in table 7. These submerged ice thicknesses, measured at a variety of locations, suggest that by mid-January the ice was typically 0.80 m. This thickness increased to 0.92 m by early March and remained at that thickness into April. Compared to previous years (Andres and Rickert, 1984) the ice thickness this year was about average. This is inspite of the above average snowfall and air temperature.

The discharge measurements made by WSC are also summarized on table 7. The Manning roughness coefficient of the ice cover shows considerable variability between the January measurement and the later two measurements, decreasing from 0.056 to 0.031. This may be due to the change in the location of the measurement or it also may be attributed to an extremely rough freeze-up and a gradual smoothing of the ice cover as the winter progressed.

5.2 Breakup Observations

Breakup appeared to begin on April 15 when three distinct short ice runs[1], each approximately 3 km in length, were observed between Grand Rapids and Cascade Rapids. At 09:30, on April 16, a 7 km long jam[1] was observed to be lodged at Cascade Rapids. Downstream of there the ice cover was solid. This solid ice extended at least as far downstream as Fort McMurray.

5.2.1 Ice Jam Formation

Sometime after 09:30 the jam at Cascade Rapids released and at 16:00 the toe for the ice run was observed passing the MacEwan Bridge (figure 13). This surge of ice was preceded by a surge of water some two hours earlier at 14:00. This surges of water lifted the ice at the bridge by about 0.5 m without breaking the cover. Immediately prior to

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[1]Personal Communication, H. Rickert, Alberta Environment

Table 7 Hydraulic characteristics of the Athabasca River near Fort McMurray during the winter of 1986-87

	Date		
	January 14*	March 9**	April 7 **
Discharge, Q (m^3/s)	143	112	147
Flow Area, A (m^2)	276	254	298
Top Width, W (m)	140	285	295
Hydraulic Radius, R_o (m)	0.99	0.45	0.51
Ice Thickness, t (m)			
- minimum	0.65	0.65	0.75
- maximum	1.15	1.10	1.05
- average[1]	0.80	0.92	0.92
Water Surface Slope[1,2] S (m/km)	0.47	0.47	0.47
Composite Roughness, n_o	.042	.029	.028
Ice Cover Roughness[3], n_i	.056	.032	.031

Note: *Measurement made by WSC at or near gauge station 07DA001
**Measurement made by WSC above MacEwan Bridge
[1]Cross-sectionally averaged value
[2]Based on ARC open water profile
[3]Computed by the Sabaneev equation with a bed roughness, n_b, of 0.025

the arrival of the toe of the moving ice, the stage rose by about 2 m over a period of about 0.5 hours. Once the toe of the running ice moved passed the bridge the stage increased further to a maximum elevation of 246.5 m, some 4.5 above the pre-breakup water level at the bridge.

Similar fluctuations were not apparent at the WSC gauge (figure 14). The clock on the recorder was about one hour slow and after correcting for this it appears that the first stage rise was at about 15:00 hours or about one hour after the first stage increase was apparent at the bridge.

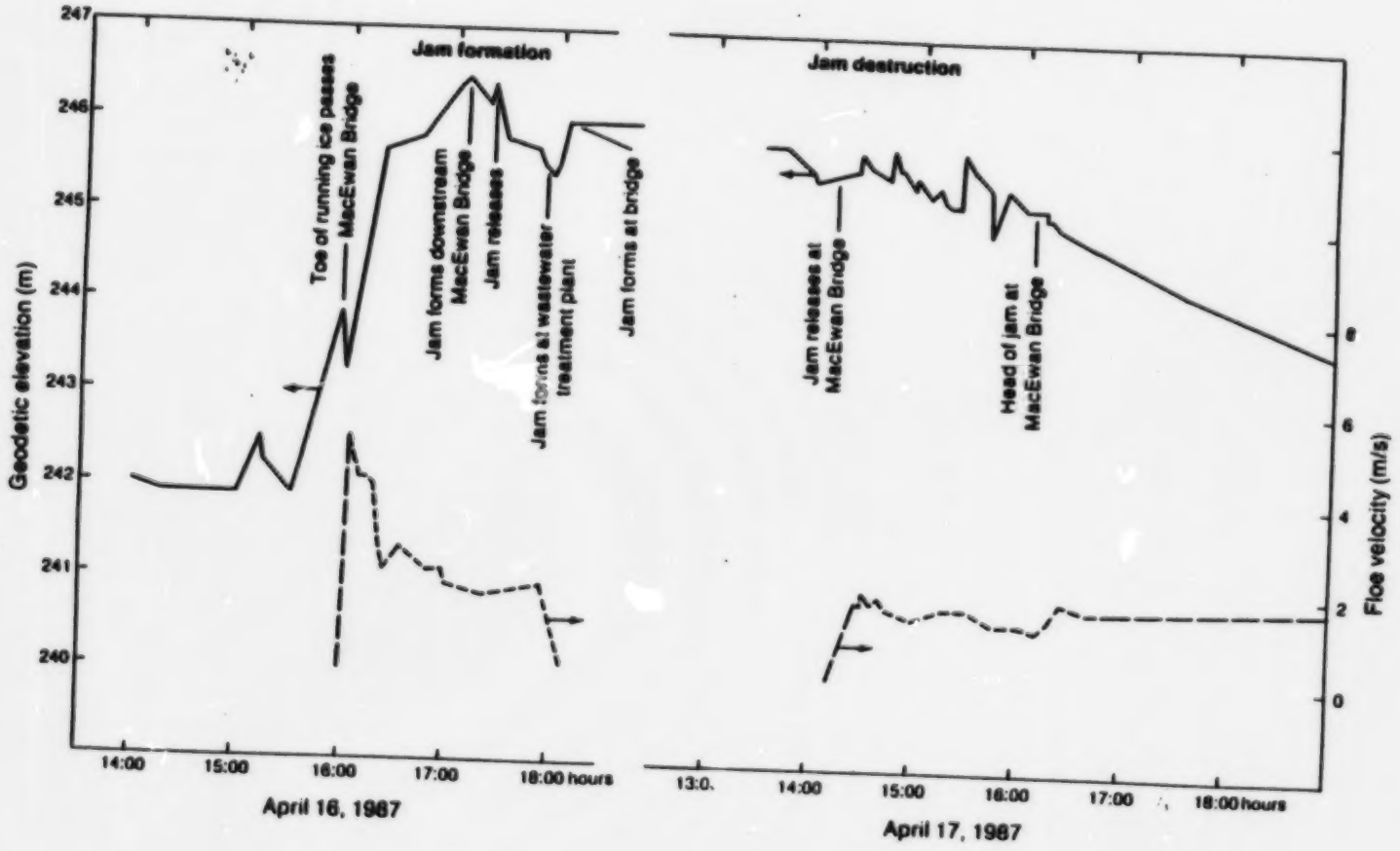


Figure 13 Velocity and stage fluctuations during the ice run and collapse of the ice jam at MacEwan Bridge, April 1987.

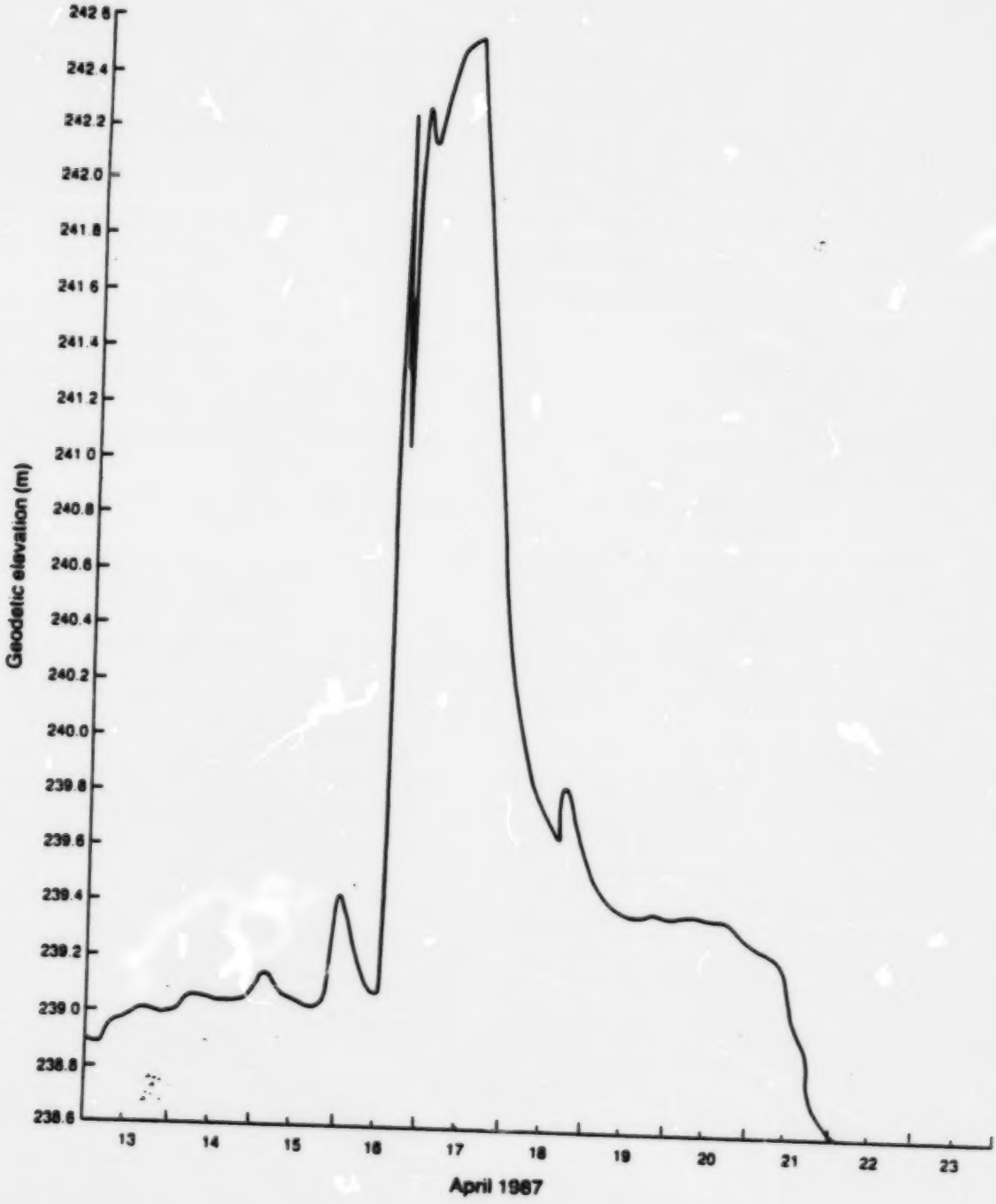


Figure 14 Water levels at the WSC Gauge #07DA001 during breakup on the Athabasca River, April 1987.

This suggests a wave celerity of about 1.4 m/s. It is also apparent that the minor surge noticed at the bridge (prior to the arrival of the main surge of water associated with the ice run) could not be discerned from the strip chart record or else it was purely a local phenomenon at the bridge only.

At 17:00 hours (time corrected) there appeared to be a significant fluctuation on the water level of the WSC gauge. This probably indicates the passage of the toe of the moving ice, suggesting an ice run velocity of about 1.4 m, similar to that of the water wave. It should be noted that stage recordings at the bridge were not made continuously, but at intervals varying between 10 and 20 minutes. Thus estimates of the celerities of the ice and water between MacEwan Bridge and the WSC gauge are approximately only.

Getting back to the events at the bridge, at 16:04 the entire ice cover (bank to bank) was mobilized and by 16:06 the ice began to shove against the island which is located immediately downstream of the bridge. Over this two minute interval the size of the ice sheets passing the bridge were reduced quite substantially. The toe of the running ice moved past the bridge at velocity of about 5 m/s (figure 13). This decreased to about 2 m/s over a period of about 30 minutes following the initial destruction of the ice cover. Then, during the remaining 90 minutes of the run, the floes moved past the bridge at about 2 m/s until the jam formed at 18:06.

At 16:36 the ice jammed between the right bank and the second pier and also along the left side of the downstream island. At 16:52 it was reported that ice had accumulated along the left hand channel adjacent to the second island downstream of the bridge. During this time and until 18:06 hours the ice continued moving past the bridge along the left bank. Further reports indicated that at 17:54 the ice jammed at the downstream end of the sewage lagoon (near the WSC gauge) and at 18:06 the ice stopped moving at the upstream end of the island located downstream of the bridge.

At 19:00 hours a helicopter reconnaissance was undertaken to assess the situation. The toe of the broken ice cover was observed to be located just downstream of Poplar Island at km 284 (figure 15). A few large fractured but intact ice sheets were observed downstream of the toe and the channel was open downstream of there. Immediately after its formation, the jam remained in a quasi-stable state in the region extending from the toe upstream past the WSC gauge and to MacEwan Bridge until at least 19:30 hours. At about 19:45 the thickened cover began to collapse along the right bank of the channel between the toe and the WSC gauge (figure 16). Ice began to move past the toe through a narrow channel along the right bank. Most of the jam was significantly compacted and held in place by the various islands and bars along the left side of the channel. However, along the right bank, ice was peeling of from the previous intact jam such that the head of the newly-created lead/moving ice was progressing upstream at a rate of about 0.15 m/s to a point just across from the south end of the waste water treatment plant. At this location a large solid unbroken sheet of ice prevented further upstream progression of the lead (figure 17). During this time the ice jam, April 16, 1987; looking downstream to Poplar Island in the jam upstream of the large ice sheet was maintained in a consolidated and thickened form and seemed to be relatively stable (figure 18). Upstream of Moberly Rapids the jam appeared to be stable albeit with a distinctly mottled surface appearance. This suggests a rather thin cover. The head was observed to be some 5 km upstream of the MacEwan Bridge at 20:10. The overall configuration of the ice jam is shown in figure 19.

Observations at 20:15 indicated that the toe jam located downstream of Poplar Island had been dislodged and all the ice along the right bank downstream of the waste water treatment plant was gradually moving downstream past the location of the toe. At 20:17 the ice was observed to be moving at the Sawmill (km 279), but it is not known for how long this had been ongoing. At 20:19 the toe of the running ice was observed to be located at km 270, just downstream of Inglis Island.

Further observations of the ice jam configuration were suspended due to impending darkness.

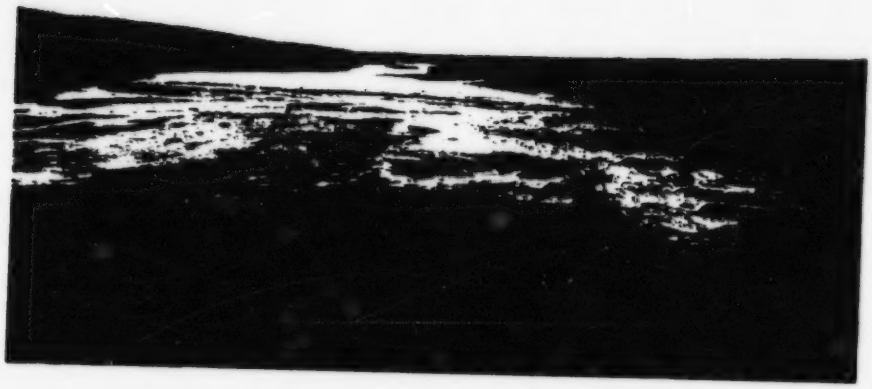


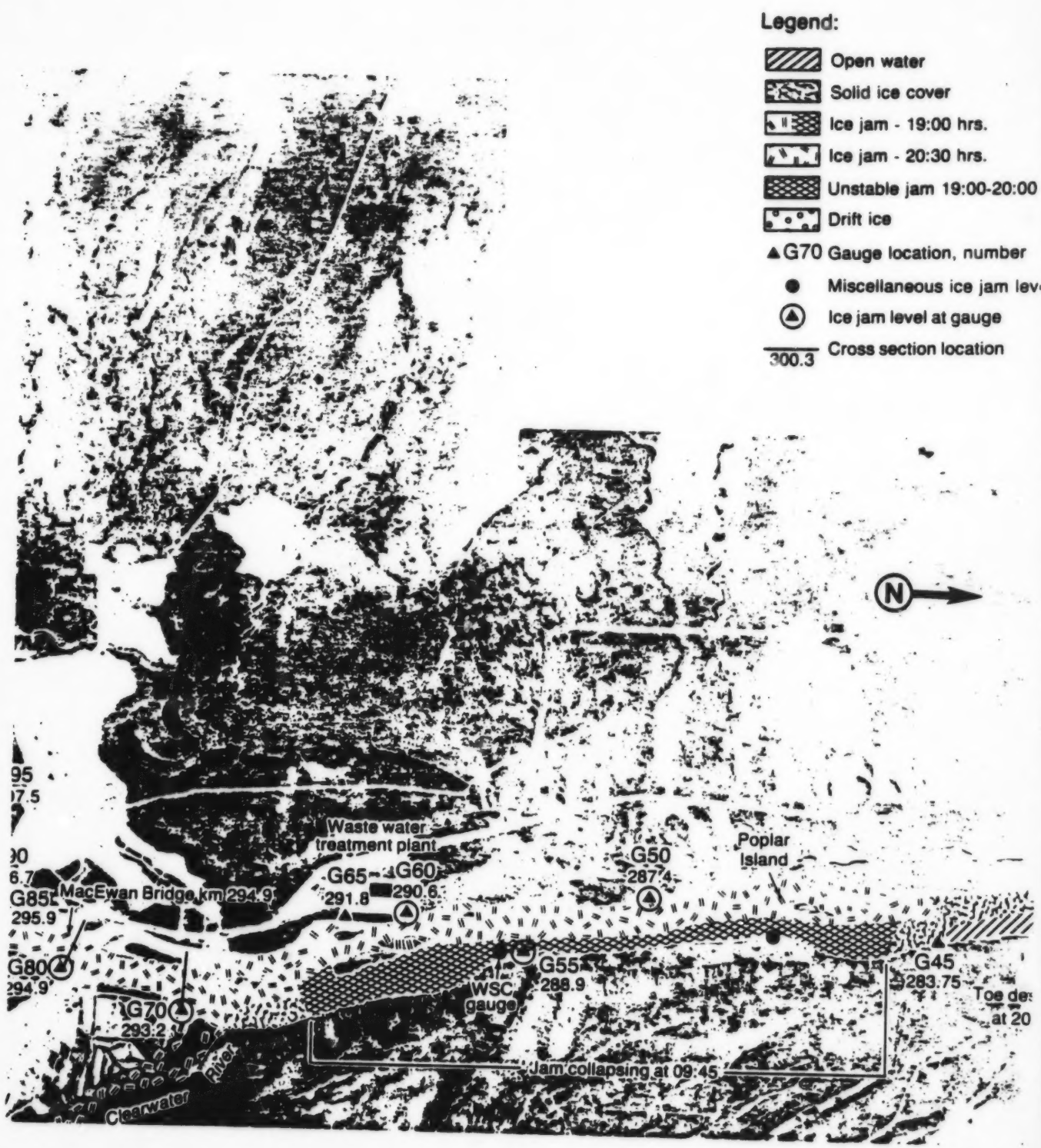
Figure 15 Toe of the initial quasi-equilibrium ice jam, April 16, 1987; looking upstream towards Poplar Island.

Figure 16 Ice moving along the right bank and passing by at toe of the ice jam, April 16, 1987.

Figure 17 Head of the open lead within the ice jam, April 16, 1987; looking upstream to the mouth of the Clearwater River.

Figure 18 Equilibrium portion of the stable ice jam, April 16, 1987; looking downstream past the mouth of the Clearwater River.

Athabasca
River
Beginning of observation
G110
303.75
G105
300.75
300.3
G100
298.7
Horse
River
Moberly
Rapids
Fort
McMurray


Legend:
Open water
Solid ice cover
Ice jam - 19:00 hrs.
Ice jam - 20:30 hrs.
Unstable jam 19:00-20:00
Drift ice
▲G70 Gauge location, number
Miscellaneous ice jam lev
Ice jam level at gauge
300.3 Cross section location
N
Waste water treatment plant
G65
291.8
G60
290.6
G50
287.4
Poplar Island
MacEwan Bridge km 294.9
G85
295.9
G80
294.9
G70
293.2
WSC gauge
G55
288.9
G45
283.75
Toe de
at 20
Jam collapsing at 09:45
Clearwater River

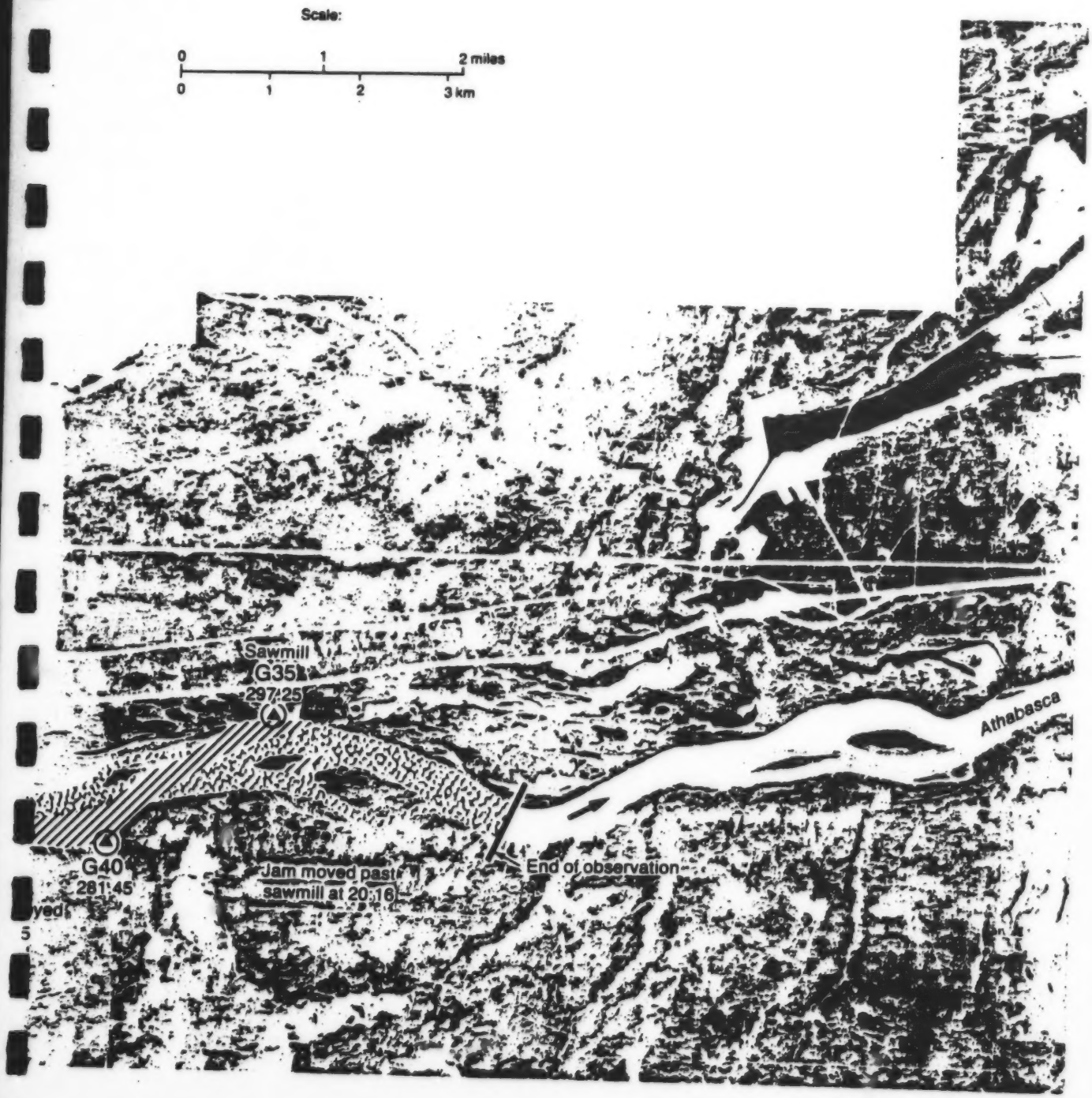

Scale:
0
1
2 miles
0
1
2
3 km
Sawmill
G35
297:25
Athabasca
G40
281:45
Jam moved past
sawmill at 20:16
End of observation

Figure 19. Configuration of the stable ice jam, April 16, 1987.

5.2.2 Ice Jam Characteristics

Ice jam water levels were surveyed from the helicopter along the length of the jam from about km 290 near the WSC gauge to km 305 near the head. This profile, shown in figure 20, represents a more or less steady condition for the period of time between 19:30 and 20:25 on April 16.

The toe of the jam was situated at km 289, approximately 1.0 km downstream of the WSC gauge. The head of the jam was located at km 302, approximately 5 km downstream of Mountain Rapids. The average water surface slope through the toe area (km 289 to km 291) appears from the profile to have been about 0.0007. The equilibrium portion of the jam (the only part amenable to simple analysis) appears to have extended from km 291 to km 301. The average slope over this 10 km distance was about 0.00047. This is the same as the open water surface slope measured during low flow open water conditions. The stage of the jam was about 4 m above typical summer open water levels and about 7 m above the mean bed level. This latter figure is somewhat arbitrary because the bed levels fluctuate dramatically within the equilibrium reach. Typical cross sections for the river reach within the equilibrium portion of the jam, along with the measured ice jam levels are shown in figure 21. This cross section information indicates that the average width, and height, through the equilibrium portion of the jam were about 370 m and 6.4 m, respectively.

Shear wall thickness were measured photographically on April 18, two days after the destruction of the jam. These measurements were made at available points of access between the mouth of the Clearwater River and the Suncor pipeline crossing. The thickness of the shear walls on the most part, varied between 4 and 5 m (figure 22) except near MacEwan Bridge. At this location the shear walls were only 2.5 m thick (figure 23). This reduced thickness was probably a result of the bank configuration and when the jam deteriorated the thick shear walls collapsed into the flow, leaving only the thin shear walls which formed well up the slope.

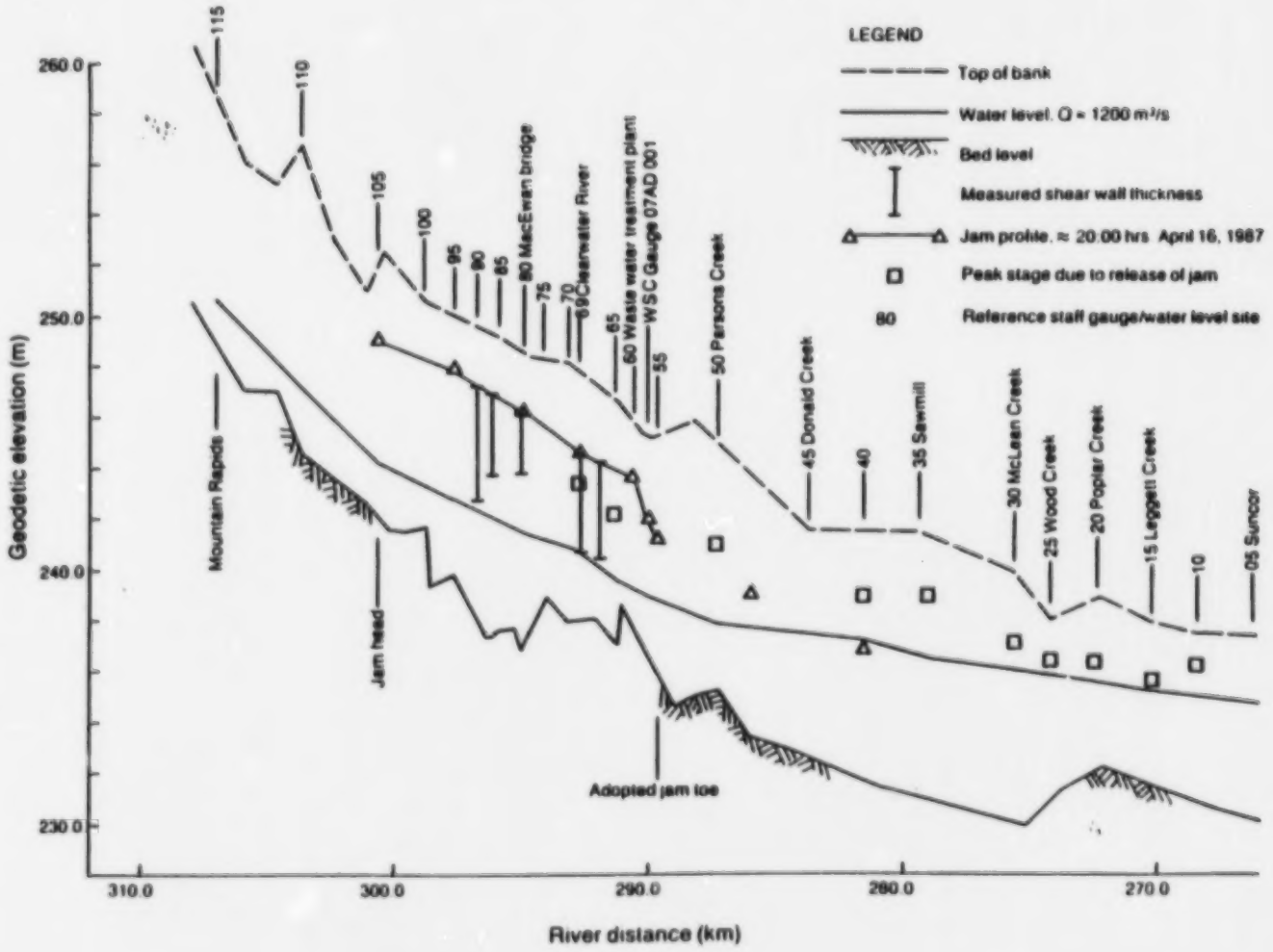


Figure 20 Ice jam profile, April 16, 1987.

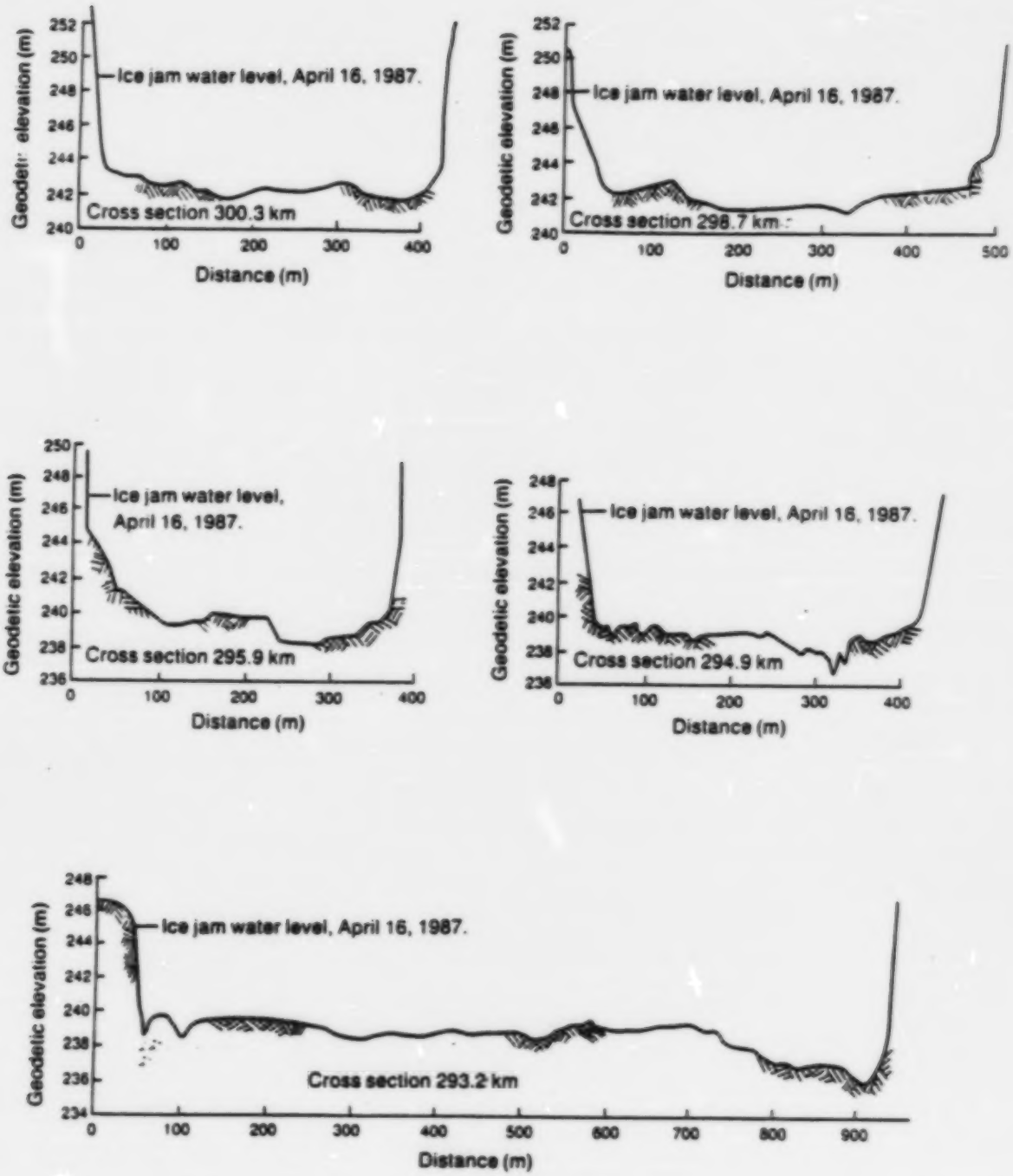

Geodetic elevation (m)
Ice jam water level, April 16, 1987.
Cross section 300.3 km
Distance (m)
Geodetic elevation (m)
Ice jam water level, April 16, 1987.
Cross section 298.7 km
Distance (m)
Geodetic elevation (m)
Ice jam water level, April 16, 1987.
Cross section 295.9 km
Distance (m)
Geodetic elevation (m)
Ice jam water level, April 16, 1987.
Cross section 294.9 km
Distance (m)
Geodetic elevation (m)
Ice jam water level, April 16, 1987.
Cross section 293.2 km
Distance (m)

Figure 21 Surveyed cross sections within the equilibrium portion of the 1987 ice jam.

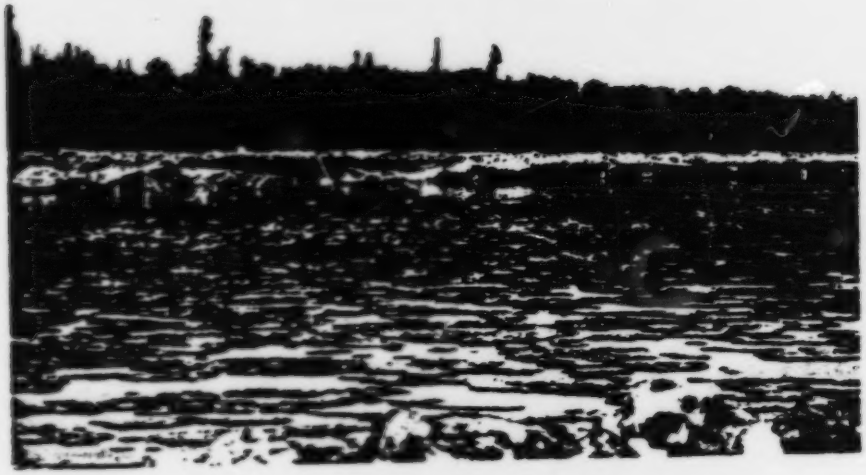


Figure 22 Typical shear walls near the Suncor pipeline crossing at Moberley Rapids.

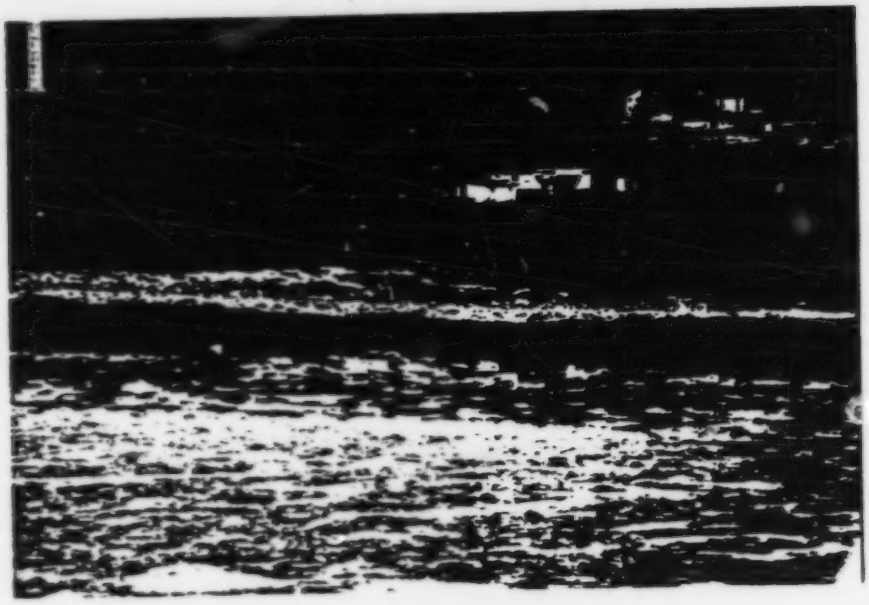


Figure 23 Typical shear walls in the vicinity of MacEwan Bridge.

Because of the very dynamic nature of the distruction of the ice cover downstream of the WSC gauge, no representative water levels could be measured from which to estimate discharges. This lack of discharge information precluded a rigorous stability analysis for this particular jam. Some inferences were made by adopting an ice jam thickness from the measured shear walls, assuming a roughness similar to that for the 1986 jam, and then computing the discharge. This was then be used to compute the coefficient of internal stability for a range of assumed jam thickness. Table 8 lists a range of potential hydraulic characteristics for the equilibrium portion of the jam.

Given the measured ice jam characteristics, and the subsequent calculations in table 8, it seems that the thickness should be no more than 4 m. Otherwise the calculated discharge become unrealistically low. Also, the low μ resulting from this conservative assumption suggests that the jam was somewhat thinner and the discharge larger. The published WSC mean discharge for the day on which the jam formed is in excess of

Table 8 Ice jam characteristics, 1987

Slope, S (mm)		0.00047	
Width, N (m)		370	
Height, H (m)		6.4	
Adopted Thickness, t (m)	4.0	4.5	5.0
Flow Area, A (m^2)	880	700	510
Bed Roughness, n_b	0.025	0.025	0.025
Ice Roughness, n_i	0.109	0.109	0.109
Composite Roughness, n_o	0.074	0.074	0.074
Computed Discharge, Q (m^3/s)	470	320	188
Hydraulic Radius (bed), R_b(m)	0.24	0.19	0.14
Hydraulic Radius (ice), R_i(m)	2.16	1.71	1.26
Coefficient of Internal Friction, μ	0.92	0.72	0.60

1000 m^3/s (taking into account flow in the Clearwater River). This is more than double that estimated herein.

As an alternative, assuming that a discharge of 1000 m3/s was the formative discharge for the measured ice jam and using the 1986 estimates of the roughness, the computed thickness would be in the order of 3.6 m. It subsequent follows that the coefficient of internal friction would have a value of 1.1. This is also a reasonable value.

It is apparent that μ is relatively insensitive to variations in discharge and jam thickness and therefore should not be used as a technique to estimate the formative discharge. Because of the lack of good discharge data, the 1987 ice jam data is only of limited value and estimates of the hydraulic characteristics and the coefficient of internal friction are subjective at best.

5.2.3 Jam Destruction

The ice jam remained in place during the night of April 16 and morning of April 17. During this time the water level at the bridge fluctuated between 245.5 m and 246.0 m without a major change in the configuration of the ice jam. However, during this time a majority of the ice downstream of the toe of the stable jam (km 290) cleared itself and moved downstream.

At 14:00 on April 17 there was a 0.2 m increase in stage of the MacEwan Bridge and at 14:13 the ice began to move downstream at the mouth of the Clearwater River. At 14:28 the ice was observed to be moving at MacEwan Bridge with the floe velocities accelerating to about 2 m/s rather rapidly (figure 13). The ice was reported to be moving at the waste water plant at about 14:30. From all appearances the whole jam seemed to have started to move downstream almost simultaneously. This suggests that consolidation was not the process of jam destruction.

Immediately after the ice began its downstream movement the stage at MacEwan Bridge began to drop. By the time the head of the pack moved past the bridge at 16:10 the stages had dropped by about 0.5 m to 245 m (figure 13). This stage reduction continued at a constant rate at least until 19:00 hours, when observations were discontinued. The head of the

pack reached the mouth of the Clearwater River at 16:48. Further observations inducted that the jam head passed the mouth of Wood Creek (km 247) at 19:55. By this time the toe was well downstream of Suncor and its locations was not observed. These reports suggest that the jam was moving downstream at about 1.7 m/s.

A helicopter reconnaissance was undertaken on the evening of April 17 to measure the peak water levels associated with the surge resulting from the failure of the jam. These water levels are shown in figure 20 and the attenuation curve is illustrated in figure 24. It is apparent that the peak stage attenuates quite rapidly when the ice jam releases into a channel of free of ice. Following the release of the jam the peak stage was reduced by one half at a distance of approximately 7 km downstream from the jam toe and at a distance of about 17 km the effects of the jam were almost imperceptible. This information lends itself quite nicely for an unsteady flow analysis to look into the hydraulics of ice jam surges. Unfortunately this analysis can become rather lengthy and it will not be addressed herein.

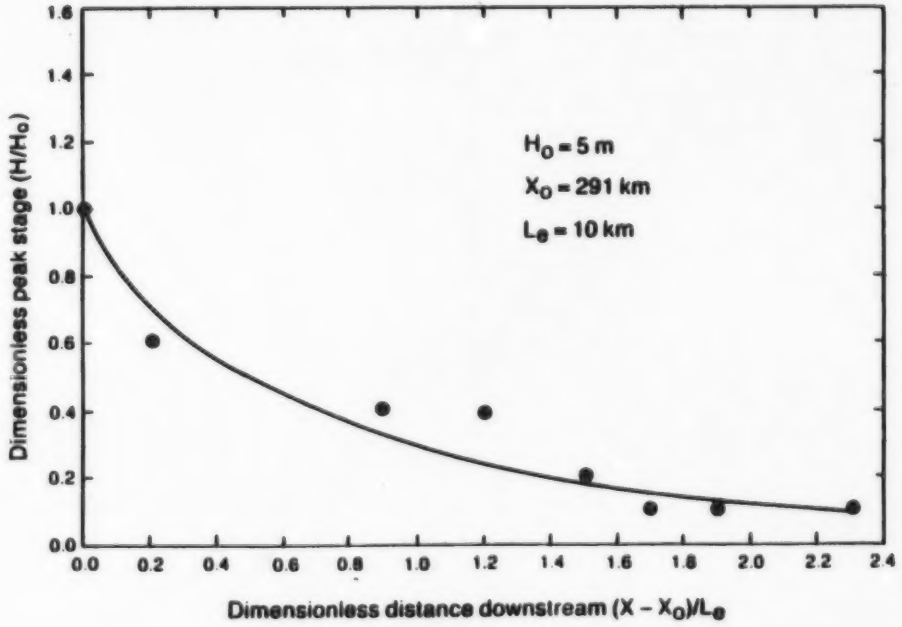


Figure 24 Attenuation of the height of the surge following the collapse of the ice jam.

6.0 SUMMARY AND CONCLUSIONS

In both 1986 and 1987, breakup of the Athabasca River ice cover was relatively uneventful for the residents of Fort McMurray. Although jamming did occur downstream of the city during both these years, either the flows in the river or the supply of ice at those time were not sufficient to produce a jam that was large enough to cause flooding. The maximum observed stage for each of those years at the mouth of the Clearwater River was 244.0 m and 244.5 m, respectively. This in the order of 1.0 m below bankfull stage on the Clearwater River.

In 1986 of the jam was located approximately 0.8 km above the mouth of Parsons Creek. The jam had total length of about 16 km and an average height (water surface to river bottom) of approximately 6.5 m. The formative discharge is estimated to have been about 540 m^3/s, of which 90 m^3/s was contributed by the Clearwater River. Computations indicate that the thickness of the equilibrium section of the jam was about 3.6 m. This is not as great as was estimated by Andres and Doyle (1984) for the jams at Fort McMurray in 1977, 1978, and 1979 but appears to be realistic given the comparatively low formative discharge. The jam roughness and coefficient of internal friction were found to be 0.074 and 1.1, respectively. Both of these values are consistent with those determined for the other documented jams along the river.

In 1987, the toe of the jam was located just downstream of the WSC gauge and the jam had a total length of about 11 km, with an average height of about 6.4 m height of the surge was about one half that of the height of the jam. At a distance of 17 km downstream the effects of the surge were almost imperceptible.

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